COMPACT HIGH POWER MICROWAVE GENERATION

A. Neuber, A. Young, M. Elsayed, J. Dickens, M. Giesselmann, M. Kristiansen
Center for Pulsed Power & Power Electronics
Department of Electrical & Computer Engineering
Texas Tech University
Box 43102, Lubbock, TX 79409-3102
Andreas.Neuber@ttu.edu

L.L. Altgilbers
US Army Forces Strategic Command
SMDC-RDTC-TDA, P.O. Box 1500
Huntsville, AL 35807
Larry.altgilbers@smdc.army.mil

ABSTRACT

The mission of the Army is evolving, which means that the weapon systems required must evolve as well. This will require a new class of munitions with either enhanced lethality or less-than-lethal capability. This requires that we develop new technologies. In order to test these new technologies to ascertain their capabilities, we need suitable test beds. One such test bed that will allow us to evaluate new types of explosive pulsed power devices, power conditioning systems, high power microwave as well as other directed energy sources, and radiators is described in this paper.

1. INTRODUCTION

One of the key factors for the generation of High Power Microwaves, HPM, is the overall system size for a given output power or energy. Typically, a narrowband HPM system consists of a pulsed power driver providing the necessary power to run the more or less efficient HPM source. While many systems have been discussed in the past, covering a wide range of HPM sources, this paper is focused on the virtual cathode oscillator, vircator. This particular source is unique in the sense that it does not require any external magnetic fields (most HPM source do), be it pulsed and permanent, for guiding the microwave generating electron beam propagating in vacuum. Although permanent magnets do not require additional power as pulsed magnets do, they still add to the weight and may cause problems in the day to day operation as, for instance, special, non-magnetic tools are needed to maintain such devices. On the other hand, the relative simplicity of the vircator comes at a cost. That is, the efficiency is typically limited to 5 to 15 % for the ratio of HPM power out to electrical power in. It should be noted, however, that efficiency numbers given in the literature need to be compared with caution as they often

differ widely in definition; one finds for instance HPM power over electron beam power as a possible definition. In such case, the power/energy expended for any auxiliary devices such as pulsed magnets or cooling is excluded from the efficiency calculation and very high efficiency numbers seem to be achievable. Overall, the authors consider the vircator as an alternative to more complex HPM sources if all factors that determine the overall (wall-plug) efficiency and size of the system are included.

Herein, we present experimental results and discussion of a small (< 15 cm diameter form factor) vircator driven by an explosive-driven helical flux compression generator compared to the same vircator driven by a compact, purely capacitor based, pulse generator.

In the open literature, the successful operation of an explosive driven HPM system has been reported in ref. [1] and [2]. Similar to the approach chosen here, experiments with a vircator produced 38 MW of peak radiated power with a 370 kV pulse from the conditioned output of a single FCG [1]. More recent work was based on utilizing two flux compression generators to drive a backwards wave oscillator [2], with the conditioned output of one flux compressor responsible for establishing the electron beam and the second FCG used to provide a guiding magnetic field. Results from these experiments indicate that the system was capable of radiating 1 GW of peak power. Successful vircator operation directly driven by a compact Marx generator was demonstrated to produce roughly 100 MW [3] repetitively at 10 Hz in burst mode. Both explosive-driven and conventional driven HPM generation discussed in the following is in the several 10 to 100 MW range. Further, both systems are self-contained or are easily adapted to being self-contained.

We utilize as energy and power amplifier a dual-stage Helical Flux Compression Generator (HFCG) that has been designed and tested extensively over the past

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two years. This dual-stage HFCG design has a 76-mm constant-diameter stator and employs flux trapping to couple the output of the booster stage to the peaking stage. Over 40 shots have been fielded with the HFCG coupled to various loads ranging from 1 to 3 µH of inductance. Performance assessments of those shots indicate that the HFCG is capable of amplifying input energies ranging from 100 to 200 J by a factor of 20 with an output current risetime of 6 µs.

This dual-stage HFCG has also been coupled to a power conditioning system consisting of an inductive energy store and exploding wire fuse. Testing with this system has shown that it is capable of delivering a peak power greater than 1 GW with an output pulse of at least 150-ns FWHM to a 20-Ω load. When coupled to a reflex-triode vircator, the entire system produced a peak power of 30 MW with a pulse length of 150-ns FWHM with significant frequency components ranging from 2-6 GHz. A compact Marx generator was constructed to benchmark the HFCG based system against a conventional, non-explosive design. Details of the different designs, explosive and conventional, are provided and compared.

2. EXPERIMENTAL SETUP

The self-contained HPM system based on the use of explosive-driven pulsed power was constraint by a maximum physical volume of less than 0.03 m³, with a cylindrical base shape of 0.15 m in diameter. This includes the prime source, HFCG, power conditioning, and the HPM source. No effort has been put into fitting the conventional driver, a Marx generator, into the same volume. Rather, emphasis was put on producing an output wave-shape with the Marx similar to what was observed in the explosive-driven case.

2.1 Explosive-Driven System

A 12 V lead acid battery was chosen to provide the prime energy to the pulse capacitor, which is charged to roughly 4.5 kV with 50 µF capacitance, see "A" in Fig. 1. The type of battery itself is uncritical as its volume is only about a fourth of the volume occupied by the capacitor. Some volume could be saved by utilizing primary Li-ion cells in the future.

With roughly 60 to 70% efficiency, the energy in the capacitor is then commutated into magnetic field energy as seed energy of the HFCG. The HFCG, "B" in Fig. 1, amplifies this initial seed energy by roughly a factor 20 so that the energy storage inductor has roughly 3 kJ stored by the time the fuse opens and the peaking gap closes, "C", finally commutating the inductively stored energy to the vircator, "D".
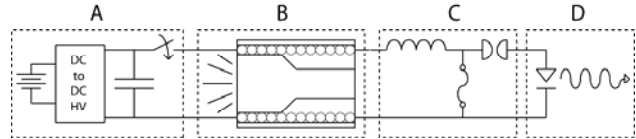

Fig. 1. Energy flow through sub-systems. Battery prime power and capacitor, HFCG, energy storage inductor with fuse opening switch and peaking gap, HPM source [4].

A cutaway view of the overall system is depicted in Fig. 2, which reveals that all subsystems fit within the prescribed volume allowance. The largest volume is occupied by the HFCG and the power conditioning system. Future volume savings are primarily possible in the prime power section by replacing the capacitor with a square foot print with a circular one, as well as shortening the power conditioning section by at least 30 %.
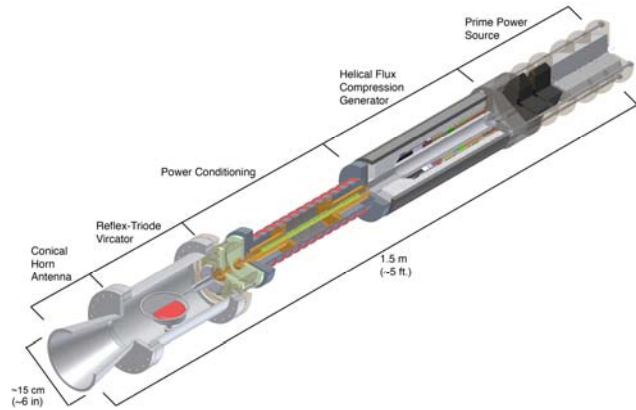

Fig. 2. Cutaway view of the overall explosive-driven HPM system [4].

In the following, the individual sub-systems of the overall high power microwave system will be briefly discussed.

2.1.1. Seed Source (A)

The compact seed source, CSS, consists of a capacitor made by SB Electronics, rated for 50 µF and 5,000 VDC. This foil capacitor with dry dielctric (no oil) has an energy density of about 600 mJ/cm³. The capacitor is charged to somewhere between 4 and 5 kV depending on the desired output energy of the overall explosive system. The required energy is provided by the battery integrated into the CSS, see Fig. 3. Currently, an off-the-shelf lead acid battery is used, which could be for further weight and size reduction replaced by a thermal or Li-ion battery. In the present design, it would be simply a matter of replacing one battery by another more advanced. The 12 V output voltage of the battery are stepped up to a maximum of 5 kV by four DC/DC high voltage converters, again off-the-shelf parts, in this case from EMCO. The four converters are placed in parallel to

increase the overall current output, thus enabling charging of the capacitor in about 30 s.
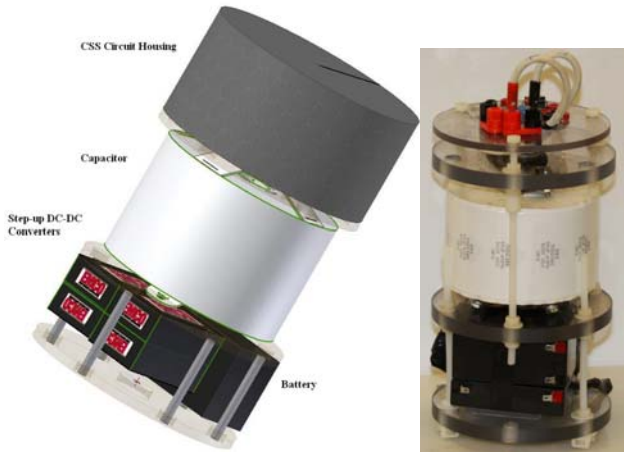

Fig. 3. Seed Source, artist rendering (left) and implementation (right), cf. Fig. 1, part A. [5]

After the capacitor is charged to the desired voltage, the energy in the capacitor needs to be switched into the flux compression generator. This is done by a semiconductor switch, a commercial high voltage BJT. Two BJT's in series are needed to hold off the 4,000 V during charging. The BJTs are triggered with a low voltage pulse (5 V TTL), and easily conduct 10 kA, see Fig. 5 in ref. [5]. Note that the BJTs are destroyed during the high current conduction, which is just fine since the overall system is meant for a one-time use to begin with. That is, a switch that could perform repetitively would unnecessarily push the cost and complexity of the CSS. Note the two spikes in the switch voltage waveform in Fig. 4, which are a consequence of the destruction of the BJTs.
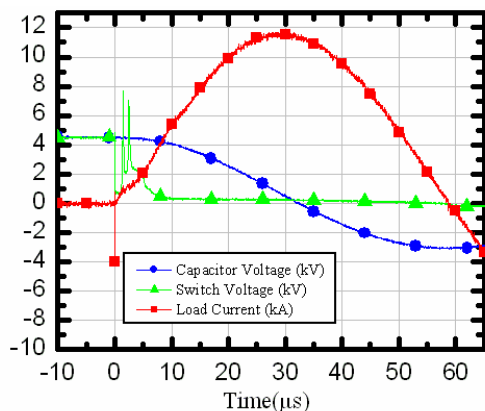

Fig. 4. CSS output using two BJTs, one being used in a "diode" configuration [5].

2.1.2. Flux Compression Generator (B)

The flux compression generator works on the same principle as any electrical generator, that is electrical conductor(s) are moved in a magnetic field. While this is done in conventional generators by rotating a coil of some sorts in a magnetic field, the flux compression generator accomplishes a similar feat by explosively moving and deforming conductors again in a magnetic field. The moving conductor in Fig. 5 is a hollow metal tube (armature) filled with HE. The HE is detonated from the left causing the tube to expand and make contact with the surrounding coils. The combined radial movement of the armature (~ 2 mm/µs) and the detonation velocity (8 mm/µs) in axial direction cause the armature to form a cone that propagates towards the right in Fig. 5. The initial magnetic field needed for operation is generated by a field coil (booster stage seed coil in Fig. 5) that is energized by the CSS.

One can show that, if there are no losses in wires etc., that the magnetic flux is conserved in such a situation, hence the name magnetic *flux* compression. An overview and more in-depth treatment of explosively driven flux compression generators can be found in ref. [6].
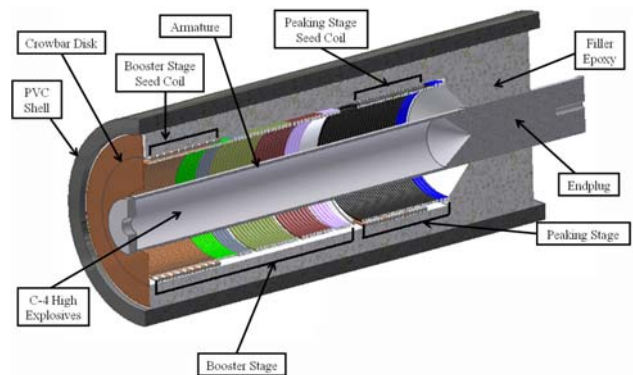

Fig. 5. Cutaway-view of dual stage helical flux compression generator, cf. Fig. 1 part B, with an explosive charge of ~ 410 g of C-4. Overall length about 30 cm (12 in).

The flux compression generator utilized here occupied an overall volume of 7 ltr, had a helical coil (stator) diameter of 76 mm, and an armature diameter of 38 mm. To protect equipment and to be able to re-utilize the non-explosive subsystems during the development phase, only the helical flux compression generator was placed inside a blast chamber, see Fig. 6.

Fig. 6. Helical flux compression generator ready to be placed into the explosive chamber.

The flux compression generator is fired into the energy storage inductor of the power conditioning system. This inductor has typically a value of a few µH and has to be able to handle several 10 kA of current, see Fig. 7, with as little loss as possible. The flux compression generator cannot be fired directly into the high power microwave source since the output impedances are different. That is, the flux compression generator tends to produce high currents (100s of kA) at comparatively low voltage levels while the selected HPM source operates at a few 100 kV but lower current. Hence, some power conditioning is needed.
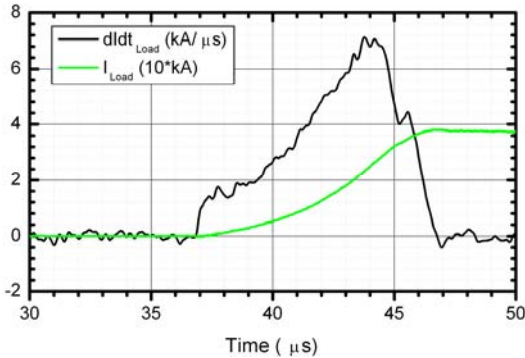

Fig. 7. Flux compression generator output current and current derivative waveforms into a 3 µH inductive load; maximum current approaching 40 kA.

2.1.3. Power Conditioning System (C)

After explosively amplifying the energy initially provided by the battery, the energy is stored in the energy storage inductor, see Fig. 8. A fuse is in line with the energy storage inductor that opens at close to current maximum. The "inductive voltage kick" associated with interrupting a current through an inductor is then utilized to drive the high power microwave source. Note that the fuse opening switch, see Fig. 9, is designed to open much faster than an industrial power fuse, typically on the nanosecond time scale. "Open" in this context means a resistance significantly higher than the load that needs to be driven. That is, for a 10 Ohm load, for instance, the fuse has to open to just ~ 100 Ohm to properly function. In general, the fuse wires go from a solid to a liquid, and final vapor due to a wire temperature rise caused by resistive heating from the kA current flowing through the wires. The higher the temperature, the higher the resistance of the fuse material in general.

Length, number of fuse wires, fuse material, surrounding medium, are parameters that have to be optimized for proper fuse operation [7]. Note that the length of the fuse determines the final resistance of the opened fuse as well as the potential for re-strike, that is the unwanted condition that the fuse closes again due to electrical breakdown of the opened fuse itself caused by the high potential of the inductive voltage kick.
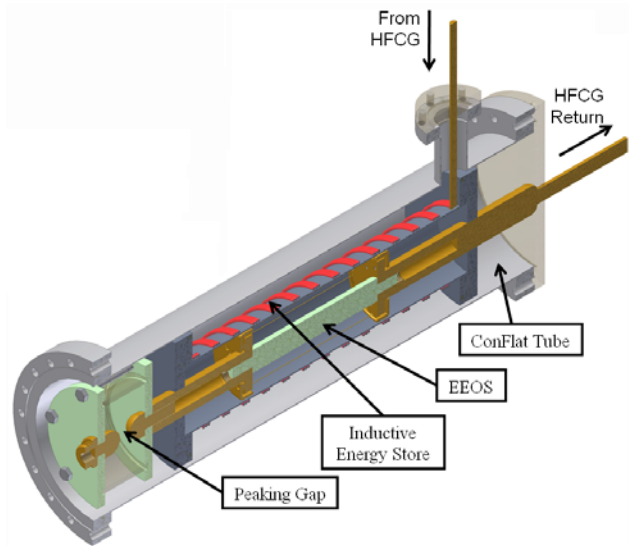

Fig. 8. Cutaway-view of Power Conditioning System with an ~ 2.25 µH energy storage inductance, cf. Fig. 1 part C. Overall length 24 cm (~ 2 ft).
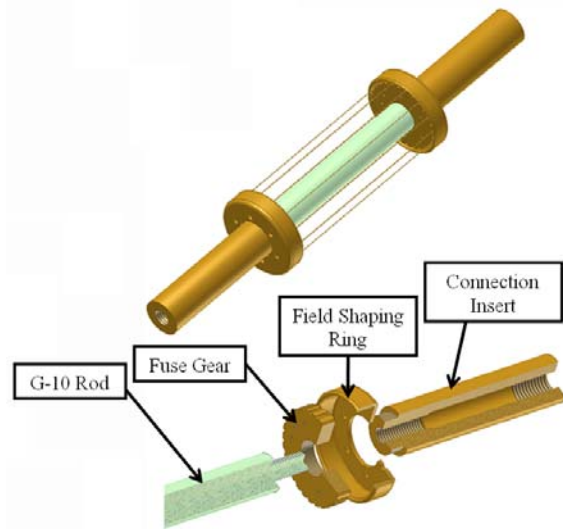

Fig. 9. Fuse opening switch detail. Typically 18 gold wires with a 127 mm diameter and 16 cm length are used for a 40 kA output current.

2.1.4. HPM Source, vircator (D)

At the heart of the virtual cathode oscillator, vircator, are a large area field emission cathode and a transparent metal mesh. Upon applying a high negative potential to the cathode (or a high positive potential to the anode if the cathode is grounded as in Fig. 10), electrons are emitted from the cathode that are accelerated to the anode mesh. Many of these electrons pass through this ~ 70% transparent mesh only to be retarded as they move farther away from the mesh. Eventually, an oscillating electron cloud, the virtual cathode, is formed on the side of the

anode away from the more tangible cathode. Any oscillating motion of charge carriers causes the emission of radiation; in this particular case electromagnetic radiation in the GHz frequency band. More in depth information on high power microwave generation can be found in ref. [8]. Note that essentially all HPM tubes require a vacuum for operation since the electron motion would otherwise be restricted by frequent collisions with gas molecules.
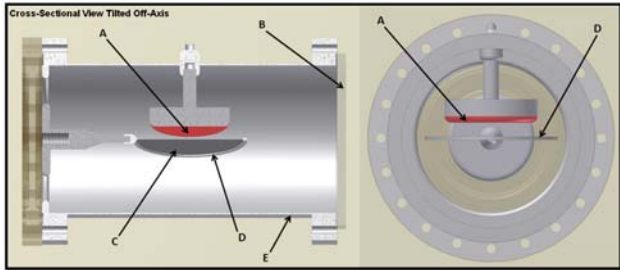

Fig. 10. Virtual cathode oscillator, cf. Fig. 1 part D. A- velvet cathode, B- microwave output window, C- anode mesh, D- anode holder, E- vacuum envelope.

In the present implementation, all subsystems, A-D, are joined with standard bolted flanges that have a diameter larger than 15 cm, which, however, can be welded in the future instead. Also, the HFCG is physically separated from the rest of the sub-systems, which enables testing the system while rebuilding just the HFCG and none of the other components. The HFCG is electrically connected via 2 larger-diameter coaxial cables as indicated in Fig. 11.
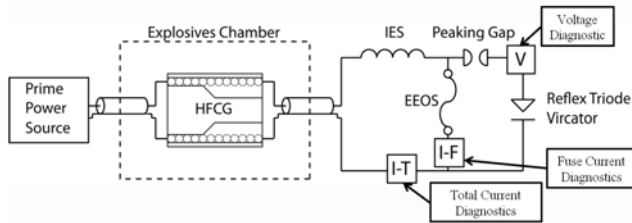

Fig. 11. Diagram of the present implementation indicating the physical separation of the HFCG from other components.

Note that this physical separation by coaxial cable introduces additional resistive losses into the system, which will disappear in any final implementation where the entire system is destroyed in each shot. The main diagnostics are commercial fast current transformers with roughly 20 ns useable risetime as well as in-house produced Rogowski coils for dI/dt measurements with a few ns temporal solution. An additional section with incorporated capacitive voltage sensor was added to the system in its experimental state between peaking gap and vircator. The impact of this section on the system's

electrical performance is estimated to be minimal. The end-on photograph of the vircator in Fig. 12 reveals the plasma formation and AK-gap closure occurring on a long time scale.
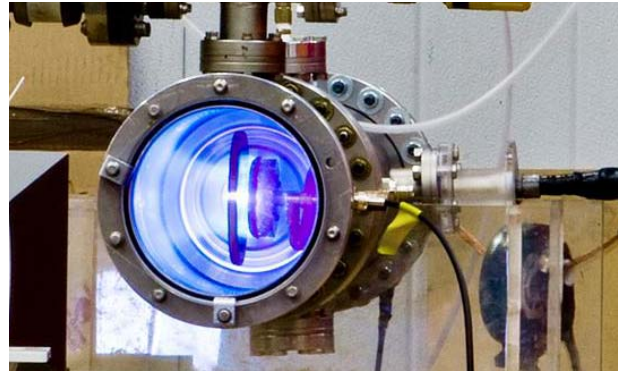

Fig. 12. Time integrated photograph of explosive-driven vircator [9].

Also visible are some flanges at the top of the vircator that serve as vacuum connections. It is planned to remove these flanges and permanent vacuum connection in a future implementation by utilizing metallic cathodes as described in ref. [3].

The electrical behavior of the flux compression generator and power conditioning system can be simulated utilizing PSPICE, see Fig. 13. Custom made models for the generator itself and the fuse opening switch have to be generated as they are not available any of the standard SPICE libraries [6].
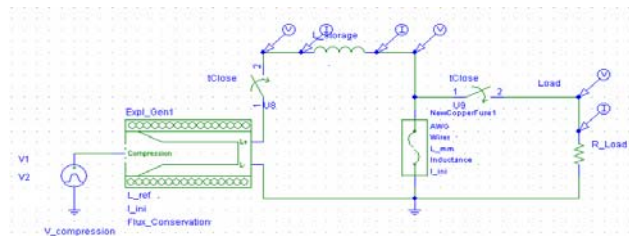

Fig. 13. PSPICE model of explosive driven high power microwave system.

2.2. Conventional System

A Marx generator [4], see Fig. 14, was built utilizing 8 Maxwell plastic case capacitors connected for charging via two continuous copper sulfate resistors visible to the left and right of the spark gap column at the top of the capacitors, see Fig. 15. The resistance per stage was approximately 10 kOhm, the capacitance was 150 nF with a maximum charging voltage of 50 kV. Due to the compactness and relatively high voltage levels, the Marx was immersed in transformer oil, visible in Fig. 16. An oil to vacuum interface is added to join the Marx with the vircator.
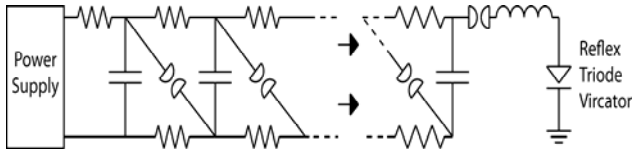
Fig. 14. Diagram of the Marx generator including the output inductor for wave shaping.

Note that the vacuum system attached to the top of the vircator, see Fig. 16, will become unnecessary with the future availability of a hard-tube device. In its present state, however, materials incompatible with a hard vacuum are used for this experimental vircator. Especially the velvet cathode, cf. Fig. 10, is a continuous source of outgassing that will spoil the vacuum quickly when active pumping is stopped.
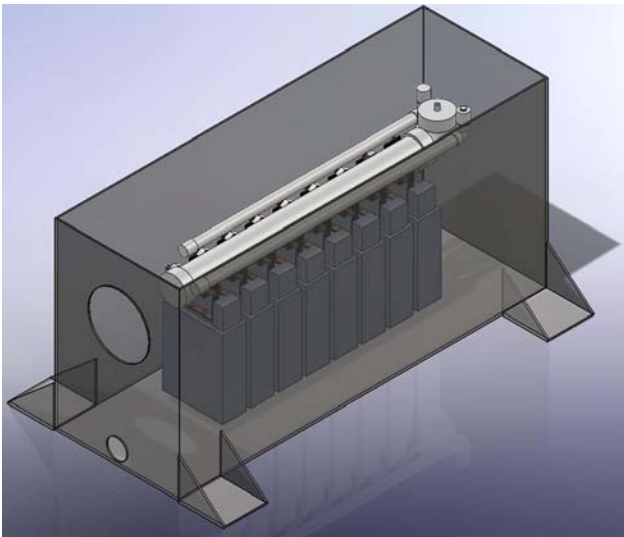

Fig. 15. Conventional pulse power driver for HPM generation (91 x 46 x 30 cm^3).
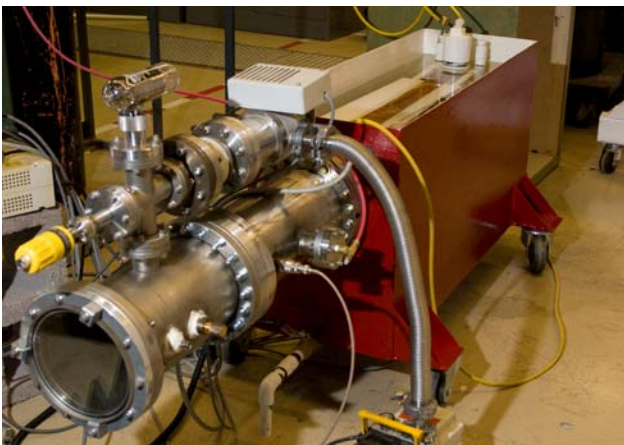

Fig. 16. Conventional driven HPM system; vircator with Marx generator in the background.

The vircator is configured in the reflex-triode geometry, with the anode pulsed positive while the cathode is held at ground potential. The microwave volume consists of a 28 cm length of ConFlat tube with the same diameter as the HFCG and the energy storage inductor section. Stainless steel wire mesh with a 70% transparency and a circular area of ~ 60 cm^2 serves as the anode, while the cathode is composed of an aluminum puck with a circular area of ~ 30 cm^2, and covered with cloth velvet material due to its high explosive emission properties. The distance between the anode and cathode is kept at roughly 8 mm. The microwaves are radially extracted with respect to the vircator's anode/cathode (axially with respect to the system's main axis), through 9.5 mm thick optical glass.

Due to the radial extraction, the electromagnetic radiation propagates primarily in the TE_{11} mode. For the experiments presented here, a roughing pump in series with a turbo pump evacuates the microwave volume to the 10^{-7} torr regime.

3. RESULTS

Along with current and voltage waveforms, the radiated electric field was measured with high temporal resolution. In the explosive driven case, a voltage pulse of roughly 140 kV with a 70 ns rise-time and a pulse width (FWHM) of 100 ns was achieved, while the total current in the system peaked at 40 kA, see Fig. 17. The pulse width of the measured microwave signal was ~100 ns, with a peak electric field on the receiving horn antenna located 4 m from the vircator output of ~13 kV/m, (see Fig. 18 with a zoomed in time scale) which gives an estimated maximum radiated power of ~ 30 MW.
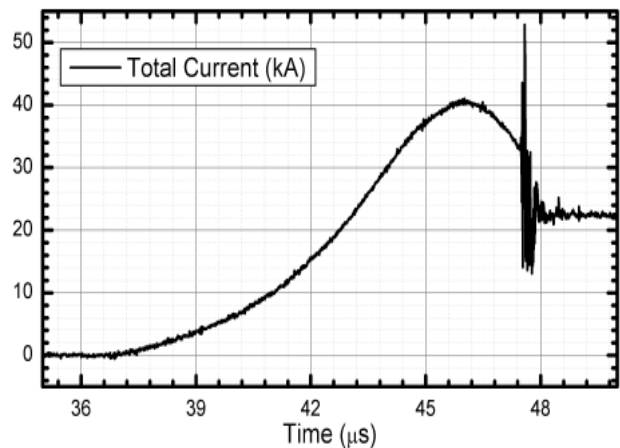

Fig. 17. Explosively-driven system; total current, I-T, cf. Fig. 11 [10].

More details of the explosive system performance into a purely resistive load are available in ref. [11].
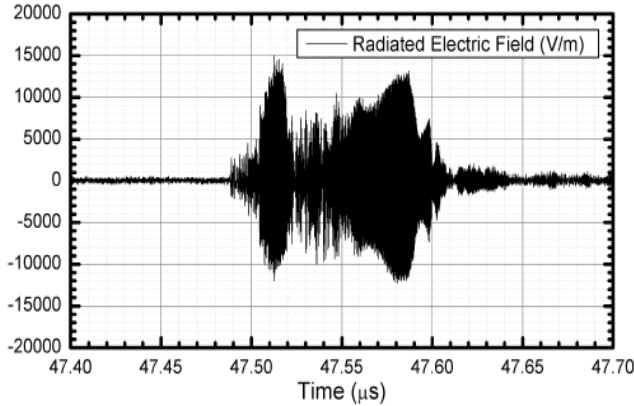
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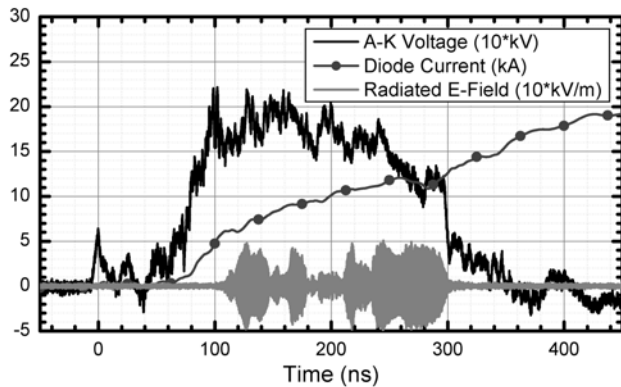Fig. 18. Explosively-driven vircator; radiated electric field [10].

Fig. 19. Conventional driven vircator; voltage (top), current (center) and microwave electric field (bottom trace) [4].

The output wave forms for the conventional driven vircator indicate a somewhat longer duration of active microwave generation, roughly 200 ns, see Fig. 19. The measured electric field of this specific shot reached 50 kV/m at a distance of 2 m. This shot had an estimated peak total radiated power of roughly 84 MW. Note that the distance between receiving horn antenna and vircator differed between the explosive and non-explosive cases. The radiated measurements were not taken inside an anechoic chamber; however, due to the short distance to the receiving antenna and much longer distance to the walls of the room, interference of the microwave signal with reflections is considered to be limited.

An FFT of the explosive driven microwave signal revealed 3.8 GHz as the main frequency component, with little frequency chirping observed in the waveforms or FFT, see left half of Fig. 20. The FFT of the conventionally driven vircator shot shows much more frequency content, with chirping from 4 GHz to almost 6 GHz. Determining the reason for the different frequency content between the two systems will be an area for future work.
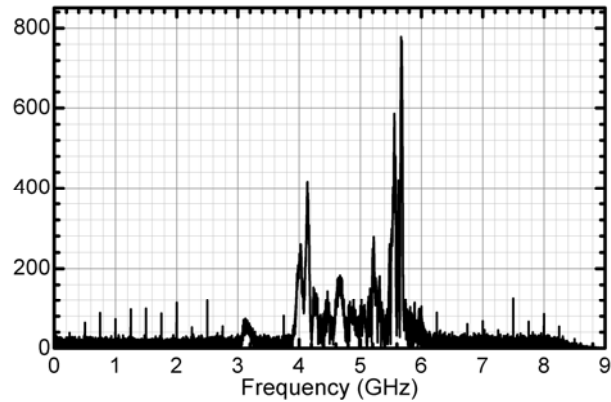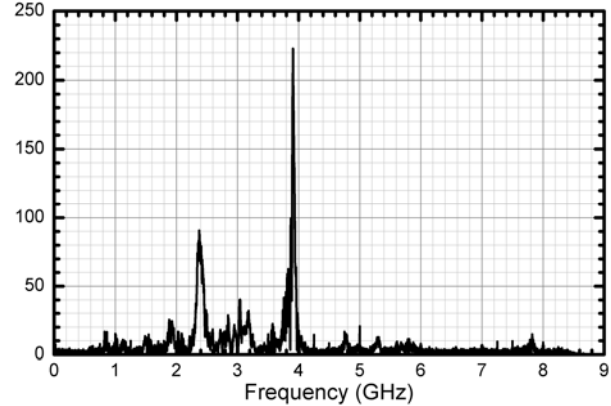

Fig. 20. Frequency spectrum of explosive driven vircator (top) and conventional driven HPM system (bottom) [4].

Overall, the explosive driven system including prime power and the vircator occupies a volume of 28 liters while the Marx volume alone without the vircator and prime power adds up to 130 liters. Adding a battery driven charging supply that would charge the Marx in about 30 seconds would add approx. another 2 liters and the vircator an additional 5 liters. This brings the ratio of explosive to conventional driven system volume to about five. It should be noted however, that the Marx was not operated at full 50 kV charging voltage to get similar voltage levels for the 2 systems. If run at full voltage, the ratio between non-explosive to explosive system volume would drop to about two. Depending on the application, the cylindrical shape of the explosive system with constant 15 cm diameter will additionally push towards the explosive implementation depending upon the specific application.

CONCLUSIONS

We have presented an autonomous High Power Microwave system that utilizes a simple battery as its sole electrical energy input. This is accomplished by explosively amplifying the initially available energy and power to the point that several 100 MW of HPM radiation is generated. To better understand the advantages of the

explosive driven HPM system over a more conventional, solely capacitor based system for energy storage, the same microwave source was also driven by a non-explosive Marx generator. Overall, the explosive system with a cylindrical shape throughput occupied less than half the volume of the conventional system with non-cylindrical base-shape. Both systems generate several 10 MW of GHz radiation with 100 to 200 ns pulse width. With refinement, it is expected in the near future to obtain a few 100 MW without increasing the size of the overall system(s). The successfully demonstrated high power microwave system is considered an important step towards a new class of munitions with either enhanced lethality or less-than-lethal capability.

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