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Experimental Observation of RF Radiation Generated by an Explosively Driven Voltage Generator

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In April of 2005, several pulsed-power experiments were performed using explosively driven voltage generation systems at Loki Inc. located in Rolla, Missouri. A pulse-forming network and transmitting antenna were constructed and attached to the voltage-pulse generator, and a matched receiving antenna was located approximately 3 m from the transmitting antenna. Three RF generation test shots were performed during the experiment. Each test shot produced two separate RF bursts. The first RF burst induced a maximum peak-to-peak signal of 30 V on the receiving antenna. The second RF burst induced a much larger signal, with a minimum of 50 V maximum peak-to-peak signal on the receiving antenna. The total pulse length was about 2μs. The effective radiated power (ERP) of the system was roughly estimated to be 2 MW in a narrow- band-pulse centered around 22 MHz. After test measurements indicate that the total power generated by the RF generator was 4.5 MW.

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EXPERIMENTAL OBSERVATION OF RF RADIATION GENERATED BY AN EXPLOSIVELY DRIVEN VOLTAGE GENERATOR

INTRODUCTION

In April 2005, several pulsed-power experiments were performed using explosively driven voltage generation systems at Loki Inc. located in Rolla, Missouri. The primary goal of these experiments was to determine the optimum explosive level and physical configuration of a piezoelectric-based, explosively driven high-voltage pulse generator, also called a ferroelectric generator (FEG). Dr. Larry Altgilbers of the U.S. Army Space and Missile Defense Command and Mr. Allen Stults at the Army Aviation and Missile Command co-sponsored these experiments. Dr. Quintin Saulter of the Office of Naval Research sponsored NRL's participation.

During the experiments, Loki Inc. was persuaded, with the permission of Dr. Altgilbers, to attach a simple pulse-forming network and a dipole transmitting antenna to the output terminals of the pulse generator. Three such explosive test shots were performed using the same antenna and pulse-forming network with FEGs that had an identical or similar physical configuration. A similar receiving antenna was placed approximately 120 in. (3 m) from the transmitting antenna, and the received waveform was observed and recorded on a Tektronix four-channel 2024 oscilloscope along with the voltage pulse delivered by the FEG to the pulse-forming network.

The three test shots produced remarkably similar RF waveforms. Each test shot produced what appeared to be two RF bursts that coincided with rapid changes in the source voltage. The first RF burst produced a peak signal of ~30 V peak-to-peak (P-P) and lasted for 1 μs. The second burst produced greater than 50 V P-P and also lasted for 1 μs. The true peak voltage of the second burst could not be determined as it saturated the input of the oscilloscope.

Peak power and power density estimates from the peak received voltage indicate that the power flux at the receiving antenna was approximately 1.64 W/cm^2 with an effective radiated power (ERP) at the source of 2 MW, assuming a near unity gain of the receiving antenna.

THE FEG AND RADIATING SYSTEM

The Loki FEG is a very compact device, as shown in Figs. 1 and 2. The FEG has an exterior dimension of 2.5 in. (6.35 cm) in diameter and is 4 in. (10.16 cm) long. This high-voltage generator is approximately the size of a soup can and has a proprietary interior design. In order to produce the high-voltage pulse, an electrically triggered explosive charge compresses a piezoelectric crystal that is connected to the output leads. For these tests the generator was powered with 25 g of stabilized cyclotrimethylenetrinitramine (RDX) (similar to C4 explosives) and had a total device weight of approximately 2 lb. Figure 1 shows the device ready for final assembly and insertion into the blast chamber. The total volume of explosive is about the size of a golf ball.

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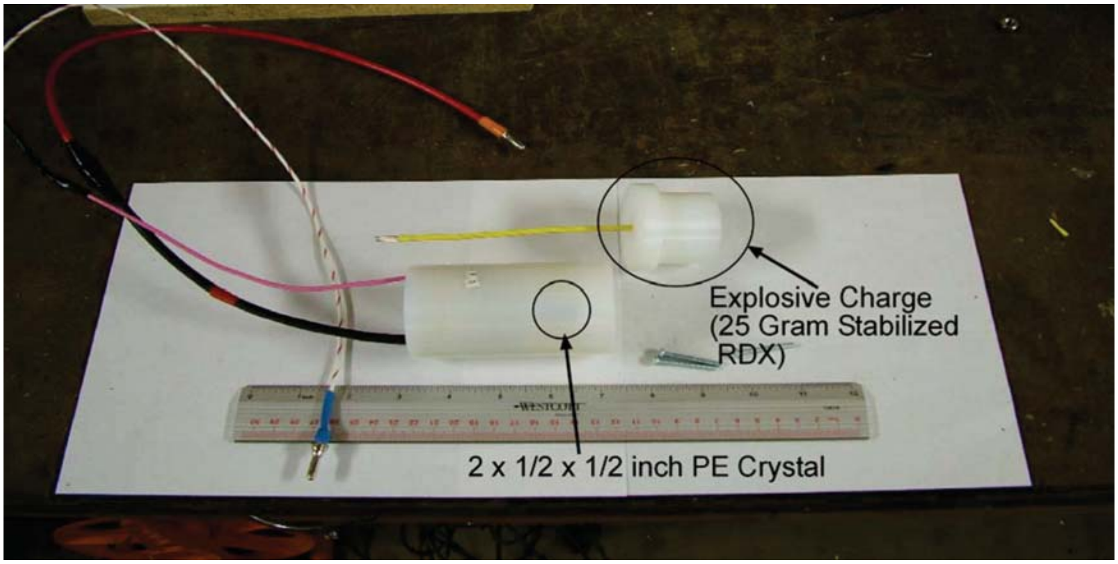

Fig. 1 — Loki FEG ready for assembly

Fig. 2 — Loki FEG assembled

Figure 2 shows a Loki FEG assembled and ready for testing. The device had a predicted peak voltage of 40 kV with the generator open circuit. This open-circuit voltage was achieved. This is a voltage yield of 3.15 kV for each mm of piezoelectric crystal thickness. This implies that a 1.25 in. (32 mm) crystal would be required to achieve a peak voltage of 100 kV. It was also found that much less than 25 g of explosive was required to achieve the same peak voltage, but 25 g net explosive weight (NEW) was used consistently in all of the RF experiments.

While observing the Loki experiments, interest was expressed in determining if the FEG would produce a significant amount of RF radiation using direct conversion methods. Loki requested that the NRL personnel attending construct a simple pulse-forming network, transmitting antenna, and receiving antenna in order to perform this experiment.

The pulse-forming network was constructed using an RG-58 coaxial cable that was 110 in. (279.4 cm) in length with 2.5 in. (6.35 cm) of the outer conductor removed from each end to prevent flashover during the high-voltage pulse. This corresponded to a total pulse-forming length of 105 in. (266.7 cm). The cable length may be used to control the frequency spectrum of the output. Later analyses at NRL indicated that the cable acts as a ¼ wave impedance matching circuit, so the system should radiate at 21.67 MHz. A spark gap was placed between the inner conductor of the coax and the dipole antenna, as shown in Fig. 3. The antenna was V-shaped, with each leg 1 m in length. The antenna shape was dictated more by the cramped test area than by any RF considerations. This should resonate at slightly less than 75 MHz, allowing for the velocity of the wave on the line.

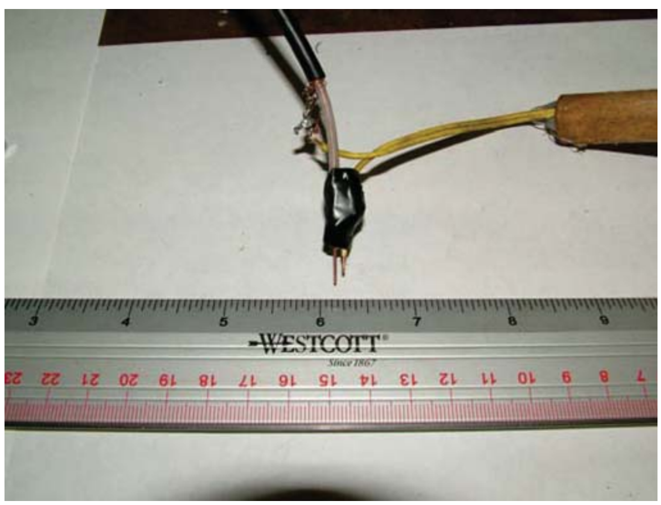

Fig. 3 — Field rigged spark gap between the radiating antenna and pulse-forming line

The receiving antenna was constructed to be similar to the transmitting antenna, and was connected directly to a 2 Giga-Sample/s Tektronix oscilloscope. Figure 4 shows the experimental layout of the system. All of the equipment, with the exception of the oscilloscope and high-voltage probe, was placed in a metal blast chamber lined with several inches of wood and other materials, all with RF absorbing properties. The tank dimensions were approximately 4 m long and 1.5 m in diameter. For two of the tests, the explosives detonator provided the external trigger to the oscilloscope. In the third test, the high-voltage pulse was used to trigger the oscilloscope.

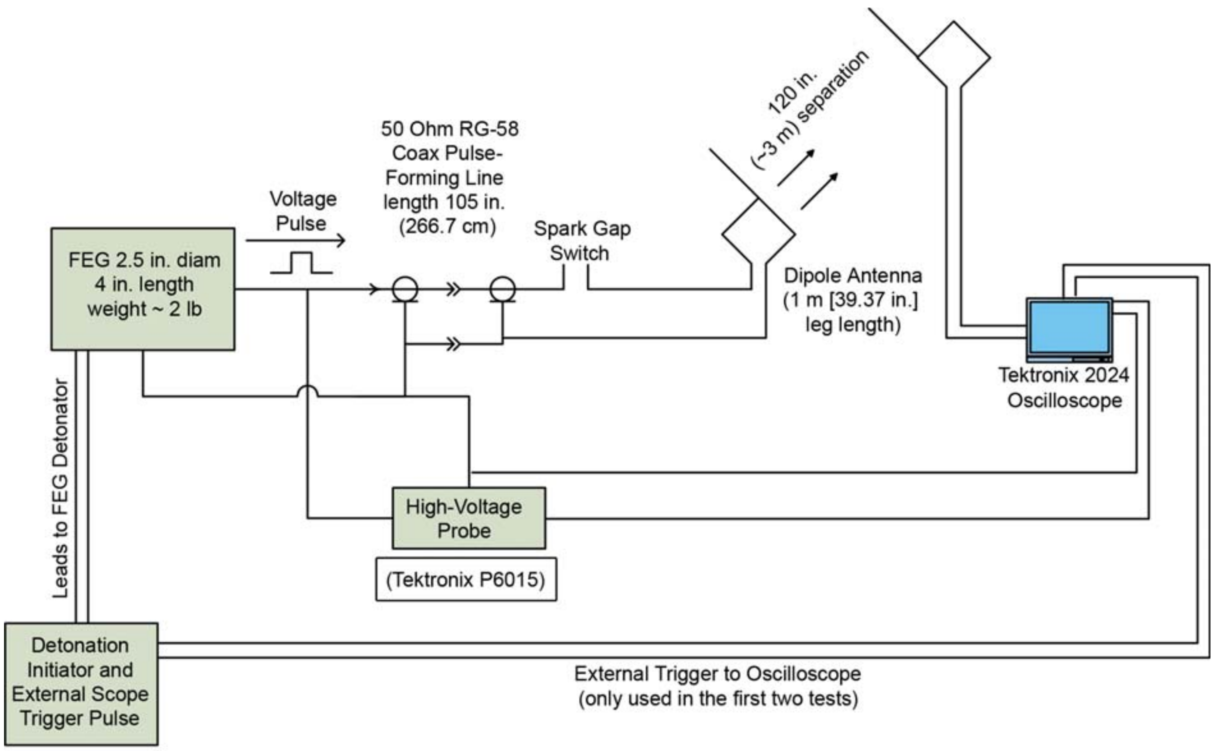

Fig. 4 — RF generation and measurement layout

RESULTS

Three tests were performed using the antenna system constructed by NRL and the pulsed-voltage system provided by Loki Inc. The test data shown in this document are from the third and final test. This data set is numerically consistent with the other two data sets and was chosen because it offers the best time resolution of the RF pulse. The sampling interval of the scope was set at 2 ns per sample.

Figure 5 shows the voltage pulse delivered by the generator to the pulse-forming network and antenna. The peak voltage, as measured by the high-voltage probe, was approximately 27 kV. This is less than the 40 kV delivered by the identical generator into a high impedance load. This reduction in the peak voltage indicates that charge and energy are flowing into the pulse-forming circuit and antenna.

Figure 6 shows the signal measured at the receiving antenna, which was located 3 m from the source antenna. The waveform seems to indicate that two distinct RF pulses were generated. The first RF pulse starts 300 ns after the voltage turn-on and lasts for 1 μs. The shape of the received pulse is consistent with a ¼ wave pulse-forming line that has been excited by an impulse function.* The maximum P-P voltage for the first received RF pulse was approximately 30 V.

The second RF pulse occurs at 1.3 μs, and produces a minimum of 50 V P-P. This second burst coincides with the disruption of the crystal lattice and a sudden drop in voltage as shown in Fig. 7. The true P-P voltage was higher than 50 V, but the value is unknown since the signal saturated the oscilloscope.

To determine the frequency content of the received signal, a fast Fourier transform (FFT) was performed on the received voltage signal. Figure 8 shows the result of that analysis. The device produced spectra with

*R.G. Brown, R.A. Sharpe, R.E. Post, and W. L. Hughes, *Lines, Waves, and Antennas, The Transmission of Electrical Energy* (The Ronald Press Company, New York, 1973), p. 104.

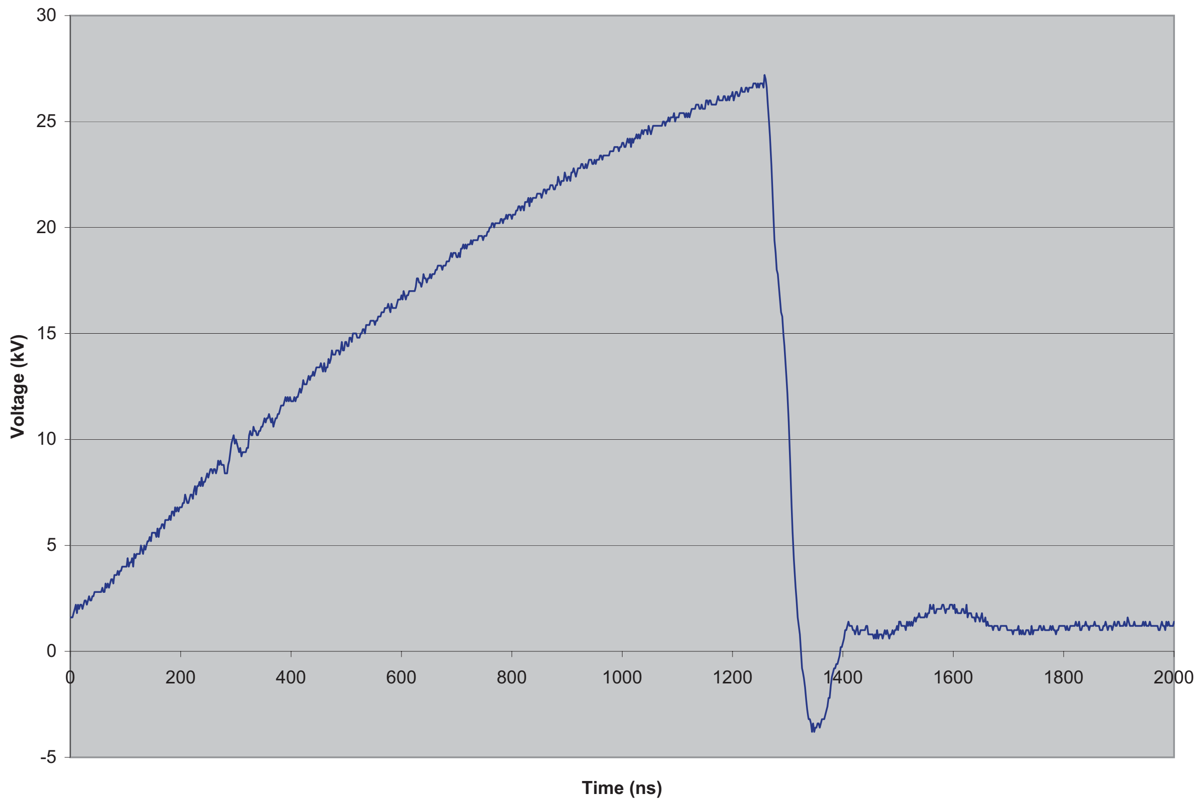

Fig. 5 — Explosively generated voltage pulse

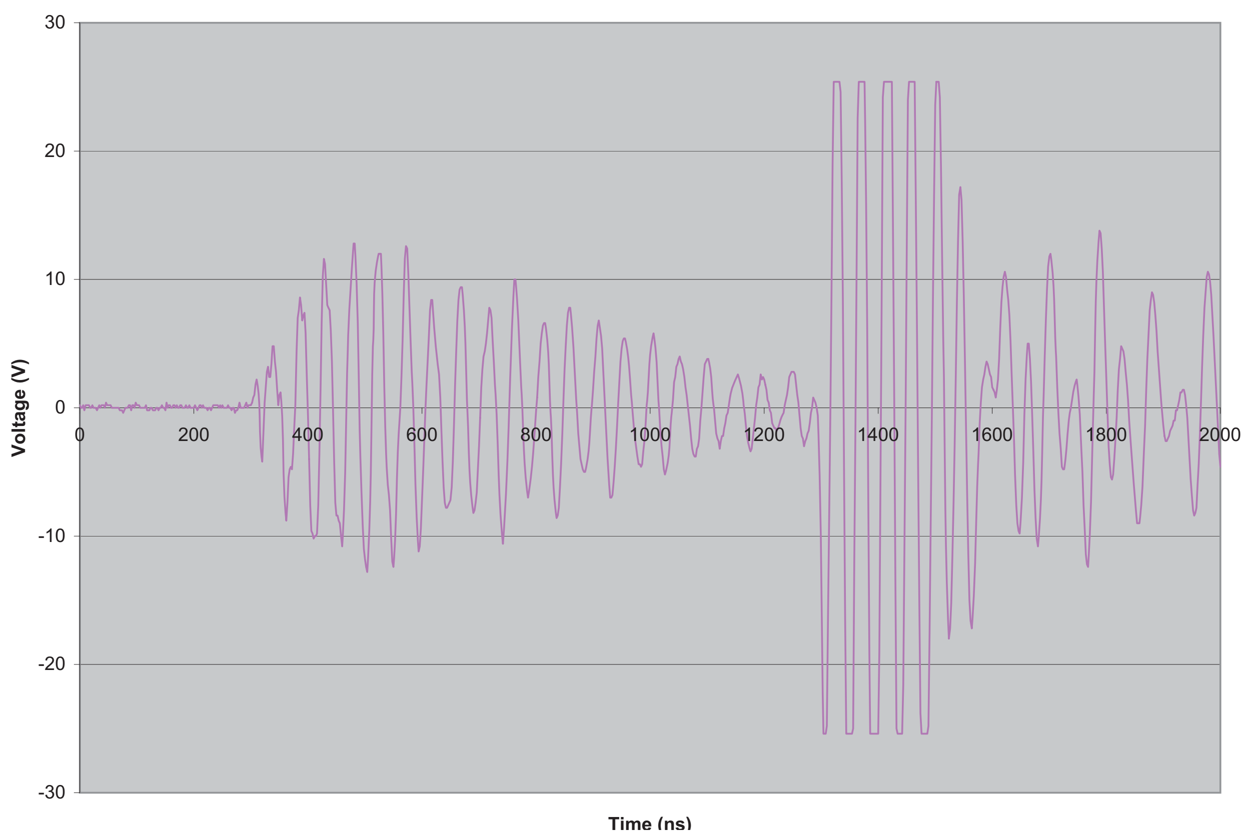

Fig. 6 — Explosively driven RF signal received 3 m from the transmitting antenna

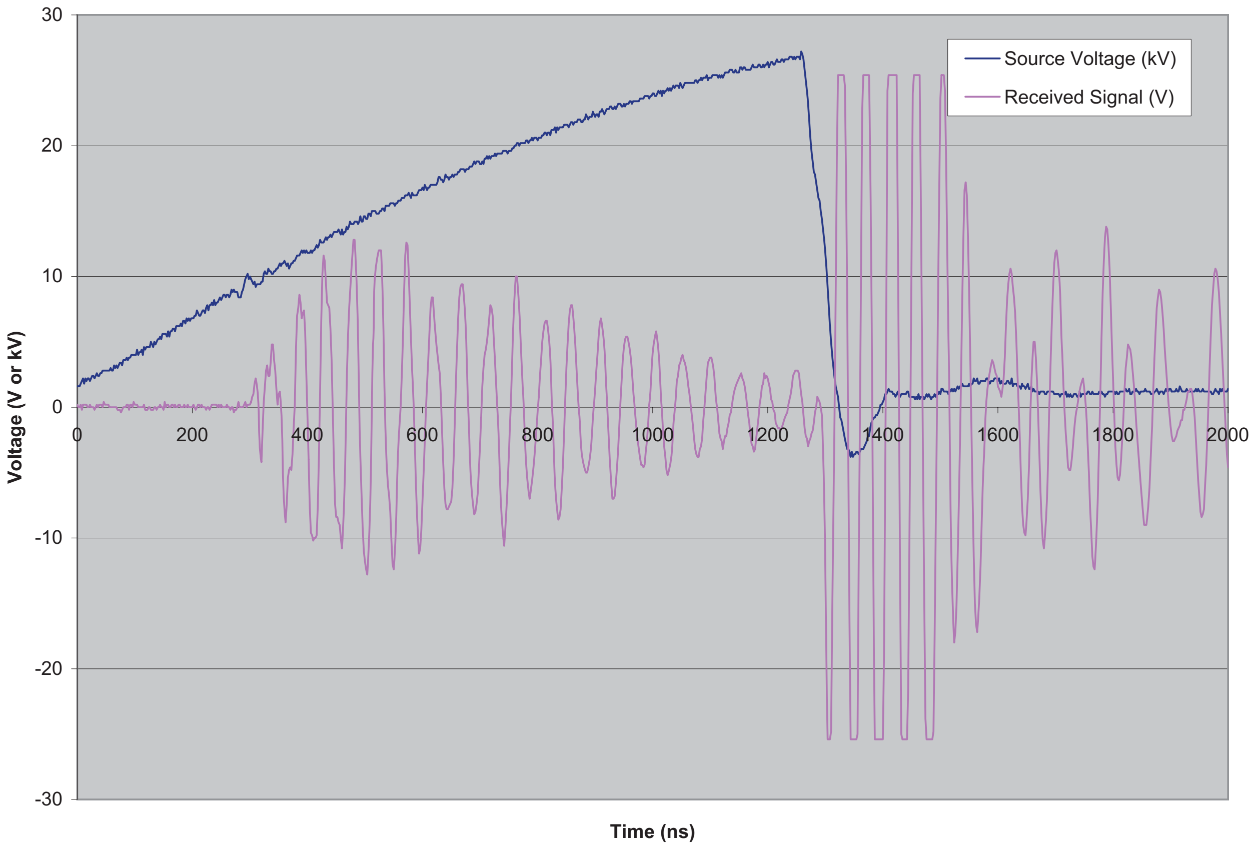

Fig. 7 — Receiver antenna signal and source voltage

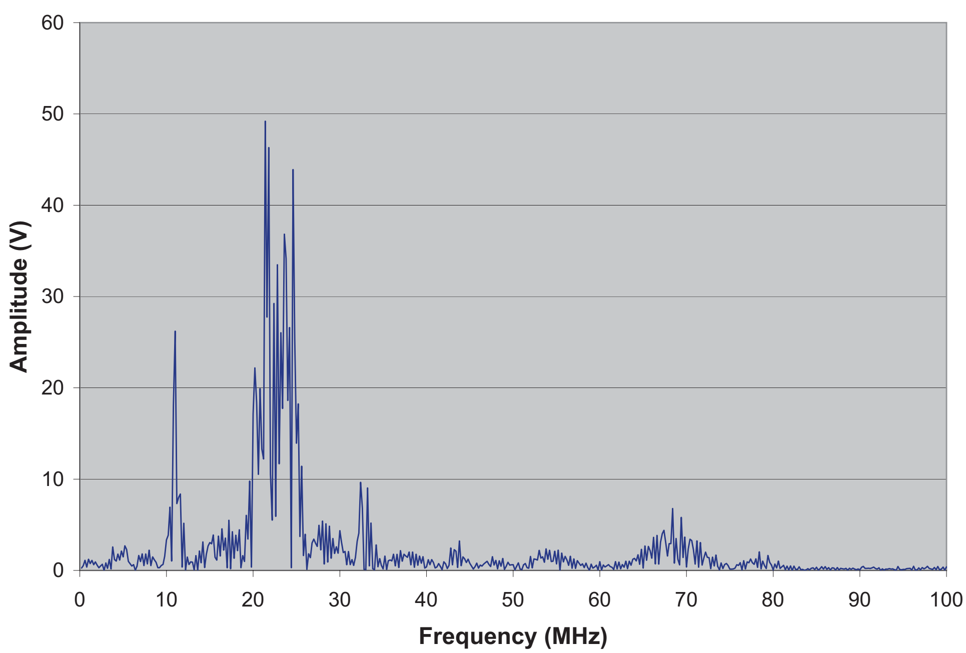

Fig. 8 — FFT of the received signal

concentration in specific areas. The largest signal occurred at 21.4 MHz. This is in good agreement with our predicted value of 21.67 MHz. The spectrum of the RF burst was concentrated between 18 and 26 MHz. It may also be noted that there is a broad spectral line centered at 69 MHz. This is in good agreement with our antenna length allowing for an antenna wave velocity 0.92% of the speed of light. A third resonance of 11 MHz is also noted. This third peak is exactly ½ of the frequency of the primary peak. We are not sure of the system resonance, which is creating this third peak.

Preliminary analysis of the received signal indicates that the system produced an ERP of 2 MW in the 18 to 26 MHz band. For an ideal dipole antenna, with open boundary conditions (0 dB gain), this would indicate that the source developed 2 MW of RF power. Unfortunately, the antennas used in the test were hastily assembled and were not optimal. Figure 9 shows the transmitting antenna and the generator inside of the blast chamber. Tests for cavity modes and return RF echoes indicate that the chamber absorbs RF radiation at the frequencies generated. Also, the dipole antennas were suboptimal, indicating that the gain would probably be less than unity.

Fig. 9 — Transmitting antenna and generator in blast chamber

In order to better determine the radiated power, the antennas were connected to a low-frequency signal generator and positioned in a similar fashion to the test conditions at the same separation distance as in the blast chamber. Low-power testing was performed to determine the power coupling and frequency response of the entire antenna system. This information was then used to determine the total RF power generated between 18 and 26 MHz. This information indicates that the total RF power generated by the device was approximately 4.5 MW over the 18 to 26 MHz band. This is in reasonable agreement with our original rough estimate of 2 MW power radiated by the system.

CONCLUSIONS

We have successfully demonstrated that explosively driven ferroelectric generators can be used to generate a significant amount of RF radiation using direct conversion methods. Approximately 4.5 MW of RF power was generated using the explosively driven FEG, and approximately 2 MW of radiated power was transmitted in a relatively long burst and a simple dipole antenna. In addition, we have shown that it is possible to predict the output frequency with reasonable accuracy. We wish to acknowledge the help of Dr. Larry Altgilbers and Loki Inc. for making this experiment possible and thank them for their efforts.