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S. I. Shkuratov

Jason Baird
Missouri University of Science and Technology, jbaird@mst.edu

E. F. Talantsev

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Sergey I. Shkuratov,[1,a)] Jason Baird,[1,2] and Evgueni F. Talantsev[3]
[1]*Loki Incorporated, Rolla, Missouri 65409, USA*
[2]*Department of Mining and Nuclear Engineering, Missouri University of Science and Technology, Rolla, Missouri 65409-0450, USA*
[3]*Pulsed Power LLC, Lubbock, Texas 79416, USA*

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The design of autonomous ultrahigh-voltage generators with no moving metallic parts based on transverse explosive shock wave depolarization of $Pb(Zr_{0.52}Ti_{0.48})O_3$ (PZT 52/48) poled ferroelectrics was explored and studied. It follows from experimental results that the output voltage produced by the shock-wave ferroelectric generators (FEGs) is directly proportional to the number of PZT 52/48 elements connected in series. It was demonstrated that miniature FEGs (volume less than 180 cm^3) were capable of reliably producing output voltage pulses with amplitudes exceeding 120 kV which is the record reported in open literature. © *2011 American Institute of Physics*. [doi:10.1063/1.3625276]

The development of miniature explosively driven ultrahigh-voltage (100 kV and up) prime power sources that are important for success of some scientific and engineering projects is an unexplored area of modern technology.[1] We are working on the development of ultrahigh-voltage prime power sources since 2000.[2] In accordance with our previous concept, the device contains two stages: a prime power stage and a pulse-transforming stage. We experimentally proved this concept earlier.[3,4] The prime power was provided by shock-wave ferroelectric generators (FEG) (Ref. 5) or shock-wave ferromagnetic generators (FMG),[6] and a vector inversion generator (VIG) (Ref. 7) was used as a pulse-transforming stage. These FMG-VIG and FEG-VIG systems were capable of producing high-voltage pulses with amplitudes up to 92 kV.[3] However, there are several disadvantages in two-stage ultrahigh-voltage generators, i.e., their complexity, large size, and weight.

In this note, we report on the results of the development of our second concept of autonomous ultrahigh-voltage generator. It is a single-stage FEG that is capable of producing ultrahigh-voltage without a pulse-transforming stage or any other power-conditioning stage. The starting point for the development of this generator was the results we obtained earlier with planar-shock-wave FEGs.[5,8] These FEGs routinely produce output voltages exceeding 25 kV. However, the presence of a explosively accelerated metallic impactor that initiates shock wave in the ferroelectric elements in the generators[5,8] significantly increases the amount of high explosives (HE) required, increases the size and weight of the generators, and becomes a limiting factor when developing miniature ultrahigh-voltage prime power sources. In Ref. 9, we reported on the detection of longitudinal and transverse shock depolarization of $Pb(Zr_{0.52}Ti_{0.48})O_3$ (PZT 52/48) ferroelectrics by cylindrical radially expanding shock waves that were generated directly from the HE detonation. These effects can be utilized for construction of axial FEGs that are capable of producing output voltage below 40 kV level.[9] In this note, we further develop our design approaches. As a result of these efforts, we developed and studied miniature FEGs that reliably generate output voltages exceeding 120 kV.

A schematic diagram of the FEG detailed in this paper is in Fig. 1. The FEG contained two parts: a detonation chamber and a ferroelectric element incorporated in a plastic body. The ferroelectric element was encapsulated with epoxy (Pacer Technology SY-SS) as the electrical insulating material. The FEGs (Fig. 1) did not contain an explosively accelerated metallic impactor used in planar-shock-wave FEGs.[5,8] The shock wave in the ferroelectric element of this FEG (Fig. 1) was generated from the HE detonation because the HE was in direct contact with the top of the plastic body. We used desensitized RDX HE (detonation velocity of 8.04 km/s and theoretical dynamic pressure at the shock front of 36.7 GPa) and RISI RP-501 exploding bridgewire detonators in the charge system.

We considered ferroelectric elements of different geometries for utilization in ultrahigh-voltage FEGs. The FEG is a prime power source of a capacitive type, and its output energy, W, is directly proportional to the square of the amplitude of the FEG mean output voltage, U_g, and to the capacitance of the ferroelectric element, C_g,

$$W = \frac{C_g U_g^2}{2}. \quad (1)$$

It follows from our experimental studies of the generation of high voltages with PZT 52/48 disk elements that the high-voltage amplitude produced by the planar-shock-wave FEGs (Refs. 5 and 8) depend on the thickness of the disk as its main parameter because the voltage depends on the thickness of the ferroelectric material between the two electrodes of the element. The electrodes are placed on the two flat surfaces of the disk element. Unfortunately, increasing the thickness of the ferroelectric disk of a given diameter results in a linear decrease of the FEG capacitance. To keep the capacitance of the thicker disk at the same level, we have to increase its diameter (and also the diameter of the electrodes). An increase of the disk diameter causes an increase in the transverse cross

a)Electronic mail: shkuratov@lokiconsult.com.

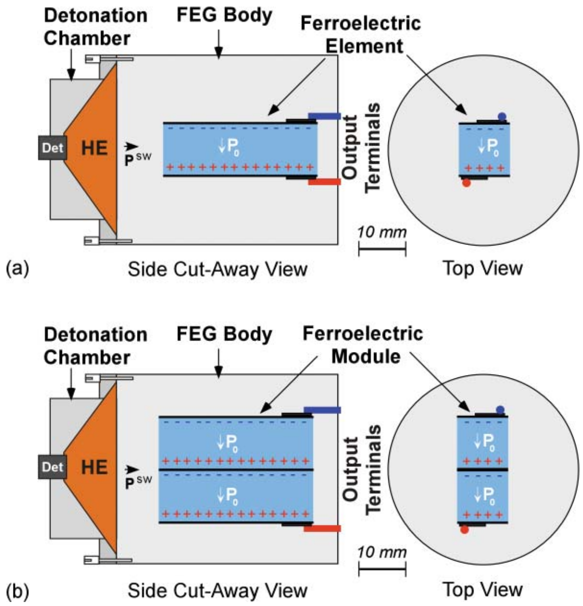

FIG. 1. (Color online) Schematic diagram of the semi-planar-shock-wave FEG containing (a) a single PZT 52/48 rectangular element (case 1) and (b) two elements connected in series (case 2). $\mathbf{P}^{SW}$ is the shock vector. $\mathbf{P}_0$ is the polarization vector. Polarity of the surface charge is shown as (+) and (−).

sectional area of the FEG, which is not appropriate for a system intended to be as small in cross section as possible. Therefore, in this paper, we investigated ultrahigh-voltage generation with ferroelectric elements of rectangular geometry (Fig. 1). With these elements, we have the opportunity to increase the capacitance of the FEG [and, correspondingly, the FEG output energy in accordance with Eq. (1)] by lengthening the rectangular elements without increasing the FEG cross sectional dimensions.

We purchased PZT 52/48 rectangular ceramic elements of 12.7 × 12.7 × 50.8 mm^3 from the ITT Corp. for these tests. The ferroelectric elements were poled across their thicknesses to their remnant polarization by the manufacturer. Parameters of PZT 52/48 were as follows: density 7.5×10^3 kg/m^3, dielectric constant $\varepsilon = 1300$, Curie temperature 320 °C, Young's modulus 7.8×10^{10} N/m^2, piezoelectric constant $d_{33} = 295 \times 10^{-12}$ C/N.

The FEG output voltage was monitored with a North Star PVM-5 high-voltage probe (resistance 400 MΩ, capacitance 12 pF) placed outside the blast chamber and connected to the output terminals of the FEG. Explosive experiments were conducted in the facilities of the Energetic Materials Research Laboratory at the Missouri University of Science and Technology.

The operation of the FEG (Fig. 1) was as follows. After initiation of the detonator, the detonation wave propagated through the HE charge and into the epoxy potting compound containing the ferroelectric element. The semi-planar shock wave front then propagated through the PZT 52/48 element, creating a mechanical stress wave in the element that depolarized it. Before the shock compression, the electric field in the ferroelectric element is equal to zero because of compensation by the surface charge (the bonded charge) of the polarization of the element, $\mathbf{P}_0$, obtained during the poling procedure. As a result of shock depolarization, shock depolarization, the surface electric charge was released at the electrodes of the PZT 52/48 element and an output voltage was generated at the output terminals of the FEG. The amplitude of the voltage pulse depended on the degree of the depolarization and physical dimensions of the PZT 52/48 ferroelectrics.

The first experimental series was performed with FEGs of 38-mm diameter (case 1 in Table I). The detonation chamber cone angle was 60°. The mass of RDX was 10.4 ± 0.7 g. A typical waveform of the output voltage produced by the FEG for case 1 is shown in Fig. 2. The amplitude of the voltage pulse was $U(t)_{\max} = 39.4$ kV with rise time $\tau = 1.6$ μs. The amplitude of the mean output voltage averaged over seven experiments of this series was $U_g = 38.7 \pm 1.2$ kV.

Recently,[9] we studied the generation of high voltage with identical PZT 52/48 elements (12.7 × 12.7 × 50.8 mm^3) in axial radially expanding shock wave FEGs. Our new FEG design (Fig. 1) provided a 60% higher voltage amplitude (Fig. 2) than we obtained from axial FEGs.[9] It follows from these experimental results that transverse semi-planar shock waves provide a higher degree of depolarization of PZT 52/48 ferroelectrics than transverse axial radially expanding shock waves.[9] Possible causes of the observed depolarization effect may be the different shock front geometry and different shock front pressure in these two cases, or the effect of shock wave splitting in PZT 52/48 ferroelectric ceramics.[10,11] It should be noted that the HE mass in axial FEGs (Ref. 9) was three times less than that in the semi-planar shock-wave FEGs described herein.

In order to increase the FEG output voltage, we connected two PZT 52/48 elements in series (case 2). A schematic diagram of the FEG is in Fig. 1(b). The negative electrode of the first element was connected to the ground terminal of the FEG. The positive electrode of the first element was electrically and mechanically connected to the negative electrode of the second element. To avoid heating the ferroelectric elements instead of using a soldering procedure, we used silver epoxy (Chemtronics CW2400) for all connections

TABLE I. Parameters of FEGs investigated in this paper.

FEG designation	Case 1	Case 2	Case 3	Case 4
Number of rectangular PZT 52/48 elements connected in series	1	2	3	4
Total thickness of PZT module (mm)	12.7	25.4	38.1	50.8
U_g, FEG mean output voltage (kV)	38.7 ± 1.2	70.4 ± 2.3	102.7 ± 3.4	123.3 ± 3.2

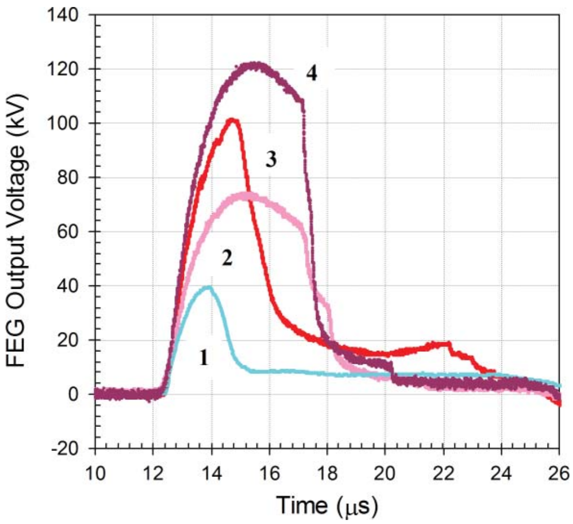

FIG. 2. (Color online) Typical waveforms of the output voltage produced by semi-planar-shock-wave FEGs containing a single PZT 52/48 rectangular element (case 1), two-element ferroelectric module (case 2), three-element module (case 3), and four-element module (case 4).

within the FEGs. The positive electrode of the second element was connected to the high-voltage output terminal of the FEG. The total thickness of the ferroelectric module was $h = 25.4$ mm. The two-element ferroelectric module (Fig. 1) contained two systems of surface charges. The positive surface charge of the first element was adjacent to the negative surface charge of the second element.

A typical waveform of the output voltage produced by the FEG for case 2 is in Fig. 2. The $U(t)_{\max} = 71.0$ kV with $\tau = 2.4$ μs. The mean voltage $U_g = 70.4 \pm 2.3$ kV. It follows from the experimental results that a twofold increase in the thickness of the PZT 52/48 module led to an increase in the FEG output voltage by a factor of 1.8. Based on these results, we conclude that there is no significant interference among the surface charges of PZT 52/48 elements connected in series during shock depolarization. This may not be the case, however, for other types of ferroelectric materials (these results are under preparation for publication).

To increase the FEG output voltage above 70 kV, we increased h to 38.1 mm by connecting three PZT 52/48 elements in series (case 3). The serial connection of the elements was made in a similar fashion to that in the two-element modules (Fig. 1). The three elements were aligned, so we increased the diameter of the FEG to 62 mm. The cone angle of the detonation chamber of this FEG was 60° and the HE mass was 59.0 ± 2.5 g.

A typical waveform of the output voltage produced by the FEG for case 3 is in Fig. 2. The amplitude of the voltage exceeded 100 kV; $U(t)_{\max} = 101$ kV with $\tau = 2.4$ μs. The mean voltage $U_g = 102.7 \pm 3.4$ kV. It is 2.65 times higher voltage than that produced by a single PZT 52/48 element with $h = 12.7$ mm. We did not observe any signs of electric breakdown within the insulation of the FEGs.

The next FEG design was based on four PZT 52/48 elements connected in series (case 4). The elements were grouped in pairs and placed in a 62 mm diameter FEG. A typical waveform of the output voltage produced by the FEG for case 4 is in Fig. 2. The mean voltage U_g produced by these FEGs was 123.3 ± 3.2 kV. We performed experiments with FEGs having different distances between the top of the FEG body and the top of the ferroelectric module. It follows from our experiments that a 30 mm potting material layer provided reliable electrical insulation in FEG design.

In conclusion, miniature sources of prime power utilizing transverse shock depolarization of $Pb(Zr_{0.52}Ti_{0.48})O_3$ ferroelectric ceramic elements by semi-planar shock waves were designed, constructed, and experimentally tested. The generators demonstrated reliable and reproducible operation. The output voltages produced by these miniature autonomous generators exceeded 120 kV, which is the greatest amplitude of the FEG output voltage ever reported in open literature.[1] These generators (patented by Loki Incorporated (Ref. 12)) can be used as sources of prime power in new scientific and engineering applications.[1]

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