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Electric field-free gas breakdown in explosively driven generators

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All known types of gas discharges require an electric field to initiate them. We are reporting on a unique type of gas breakdown in explosively driven generators that does not require an electric field. © *2010 American Institute of Physics*. [doi:10.1063/1.3460349]

All types of gas discharges previously described[1–3] require an electric field for their initiation. The electric field strength in a gas filled interelectrode gap is the main parameter that determines the probability of ionization of the gas and the generation of low-temperature plasma.[1–3] Metallic electrodes can play an important role in the gas breakdown process providing free electrons in the gas gap due to the field electron emission, secondary electron emission, or photoelectron emission. In the early 1960s, it was discovered that the laser beams can induce gas breakdown.[4,5] It was experimentally demonstrated that high-power laser beams cause plasma formation and the propagation of the plasma front in gases with no metallic electrodes in the system. The ionization of gas and the formation of plasma occur due to inelastic collisions between electrons and atoms in which the interaction energy is drawn from the electromagnetic field of the light waves. The laser-beam-induced gas breakdown was successfully used to initiate gas discharges in ultrahigh voltage spark gap switches.[5] In this brief communication, we report on experimental results that demonstrate that gas breakdown can occur with no electric field under the unique operational conditions occurring in explosively driven generators.

The electrical operation of helical flux compression generators (FCGs) is based on the magnetic flux compression inside the helical coils (stators) due to the explosively driven expansion of a cylindrical metallic armature loaded with a high explosive (HE) charge along its axis.[6–8] A schematic of a FCG is shown in Fig. 1(a). Consider the traditional model of the gas breakdown phenomenon in FCGs (most recent publications[9,10]). The model is based on the assumption that gas breakdown is caused by a high pulsed electric field, E, generated in the system due to the expansion of the armature of the FCG and the compression of the magnetic flux inside the stator [Fig. 1(a)],

$$d\phi/dt = I \cdot dL/dt + L \cdot dI/dt, \tag{1}$$

where ϕ, I, and L are magnetic flux, electric current, and inductance of the FCG, respectively.

In helical FCGs, the maximum electric fields, $E_{\max}$, is located roughly $\frac{1}{2}$ to $\frac{3}{4}$ of the distance from the contact point of the expanding armature with the stator to the beginning of the armature expansion [Fig. 1(a)]. In accordance with the aforementioned model, the gas breakdown within the FCG will occur in the region of highest electric field strength, $E_{\max}$ [Fig. 1(a)] (Ref. 10 contains detailed explanations and related references). This assumption about the location of gas breakdown at the maximum electric field region is in good agreement with known mechanisms of gas breakdown in conventional electric systems.[1–3]

It follows from the aforementioned model that with the absence of a magnetic field, B, and magnetic flux, ϕ, in the FCG, the gas breakdown should not occur because of the absence of an electric field [Eq. (1)]. Researchers apparently did not question this conclusion prior to the work reported herein, but we examined the hypothesis and believed it to be false for the following reason.

A schematic of an experiment with a FCG armature that explosively expands without any electric and magnetic field in the system is shown in Fig. 1(b). We loaded the oxygen-free high-conductivity copper cylindrical armature (outer diameter, o.d. $=50.8$ mm, inner diameter, i.d. $=46.2$ mm, and length, $h=170$ mm) at one end with a 225 g cylindrical explosive charge of desensitized RDX explosive (Chapman–Jouguet state pressure of 22.4 GPa), and we initiated the explosive charge using a single RP-501 detonator. The armature was placed inside a clear polycarbonate tube (o.d. $=82.7$ mm, i.d. $=77.0$ mm, and $h=150$ mm) that served as a model of the stator of the FCG. There were no electric potentials, electric currents, or electric and magnetic fields in the system [Fig. 1(b)]. We ignored the presence of Earth's magnetic field in these experiments due to the field's negligibly low intensity in comparison with typical values of magnetic flux density, B, in actual FCGs.[10,11] The clear plastic tube made it possible to observe, in detail, the processes occurring during explosive expansion of the armature. The tube confined the gas between the explosively expanding armature and the inner wall of the tube, in the same way that the expanding armature and stationary stator of an actual helical FCG traps gas between them. In addition, the tube

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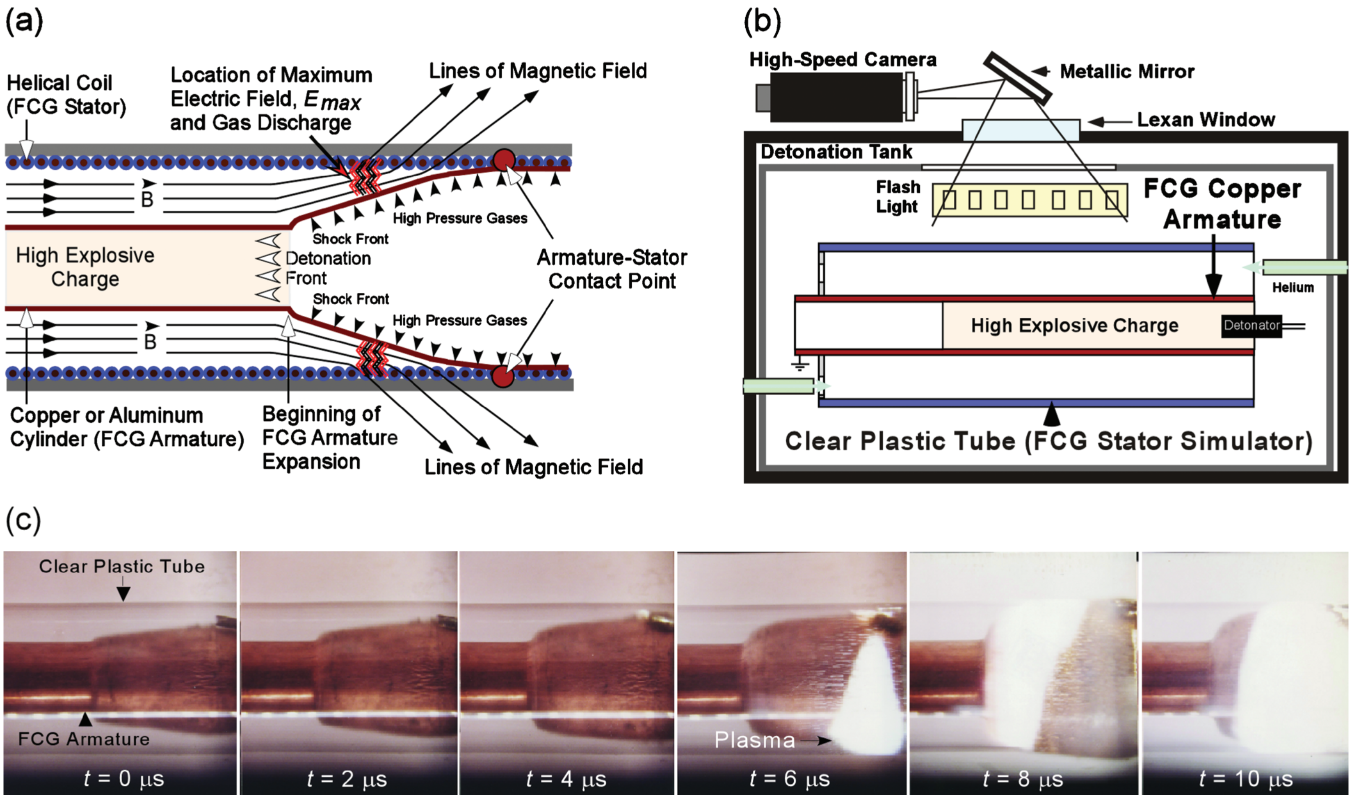

FIG. 1. (Color) (a) Diagram illustrating the explosively driven expansion of the metallic armature within the stator of helical FCG and location of the maximum electric field. (b) Schematic of the experimental setup and cut-away view of the device used for investigation of initiation of the electric discharge in gas within the FCG. (c) Series of high-speed photographs taken during explosive operation of the device shown in Fig. 1(b).

simulated the wire insulation of the coil forming the stator of a helical FCG [Figs. 1(a) and 1(b)]. We performed high-speed photography of the device's operation with a Cordin 10 A high-speed framing camera and obtained 26 frames exposed at 500 000 frames/s. To avoid shock-induced glow in the atmosphere around the device [Fig. 1(b)], we purged the test chamber with pure helium immediately before photographing the shots. Cameral synchronization and other technical details were given in Ref. 12.

Series of high-speed photographs taken during explosive operation of the device [Fig. 1(b)] are shown in Fig. 1(c); the six photographs had a 2 μs frame-to-frame interval. The operation of the system (Fig. 1) started with the point detonation of its HE charge at the end of the copper armature. The spherically expanding detonation shock within the explosive charge reached the inner wall of the armature, went through the armature thickness as an overdriven acoustic shock, and emerged from the armature outer surface. As a result of the

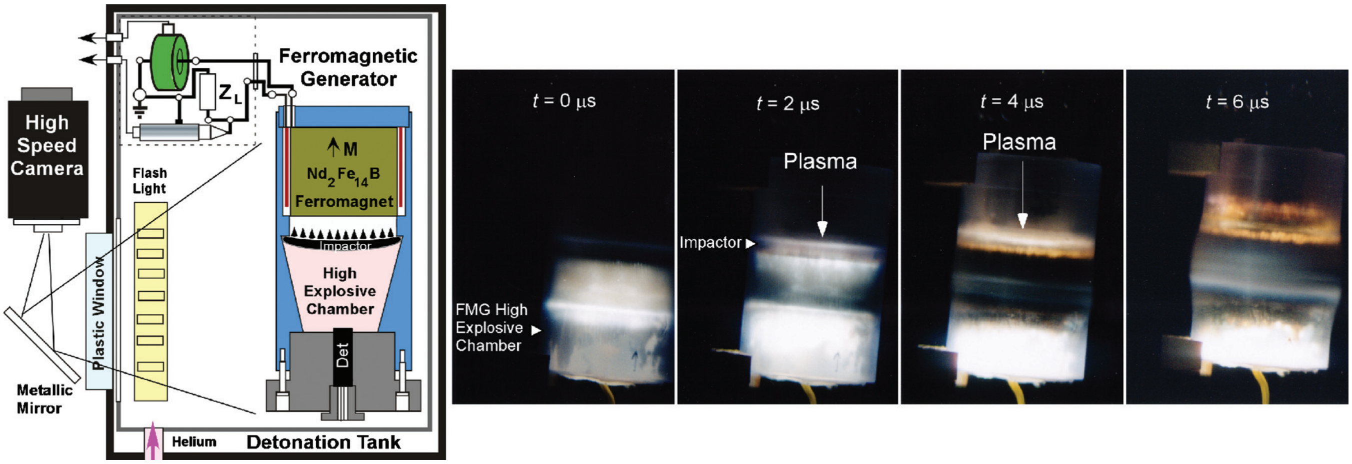

FIG. 2. (Color) Diagram of the experimental setup for high-speed photography of explosive operation of the shock wave FMG and series of high-speed photographs taken during explosive and electrical operation of the FMG.

action of the shock wave and high-pressure gases from the detonation of the HE charge inside the armature, the armature started its expansion. In the series of photographs, one can see the dynamics of an explosively expanding copper armature. Note that the explosive charge length within the armature was half the overall length of the armature so the explosive expansion stopped approximately midframe in each photograph. The radial velocity of expansion of the armature as determined by measurements from the high-speed photographs was 3.0 ± 0.1 km/s. When the explosively expanding armature approached the inner wall of the plastic tube, intense plasma formed around the expanding armature. The phenomenon documented by these photographs is direct experimental evidence of the formation of plasma and the propagation of the plasma front in the FCG purely due to the explosive motion of conductors; there were no electric or magnetic fields in the system. This means that in actual explosive driven generators the gas breakdown does not depend on the electric field strength in the system. Therefore, even with no electric field in the system or with an extremely low electric field level, it is possible to have an initial plasma in the FCG.

To demonstrate that this effect is common to all explosively driven electric generators, we performed high-speed photography of the operation of an explosive driven shock wave ferromagnetic generator (FMG).[13,14] For these experiments, we designed and constructed miniature FMGs with bodies made of a clear polycarbonate so that we could observe the processes which occurred inside the devices during explosive and electrical operations. The impact of an explosively accelerated flyer plate (Fig. 2) on the cylindrical $Nd_2Fe_{14}B$ element initiated a longitudinal (shock wave propagates along the magnetization vector $\boldsymbol{M}$) shock wave that demagnetizes the magnet.[13] We loaded the FMG with a 19 g charge of desensitized RDX and a RP-501 detonator. The diameter of the $Nd_2Fe_{14}B$ ferromagnet was 22.2 mm and its length was 25.4 mm. The 6061 aluminum flyer plate had a diameter of 25.0 mm and a thickness of 2.5 mm. Series of high-speed photographs taken during explosive operation of the FMG are presented in Fig. 2. Intense plasma formation exists ahead of the explosively accelerated flyer plate (between the impacting faces of the plate and the ferromagnetic element) at $t=2$ μs and later at $t=4$ μs (Fig. 2). It follows from our comparison of the high-speed photographs and waveforms of the voltage and current pulses produced by the ferromagnetic generator that the plasma formed prior to initiation of the shock wave in the ferromagnetic element and prior to the generation of electric signals in the FMG. This is additional experimental evidence of the formation of plasmas in explosive electric generators, in the absence of external electric fields, by explosively driven metallic elements.

Based on observed experimental fact that an electric field does not have to be present to initiate gas breakdown, which can, in turn, cause the development of intense gas discharges even when low electric fields are generated in a FCG armature-stator circuit, this breakdown phenomenon is different from all described types of gas breakdown.[1–5]

Similar gas breakdown phenomena may take place in shock wave ferromagnetic and ferroelectric generators designed with explosively accelerated metallic flyer plates. In fact, in one series of our experiments, we had difficulty obtaining signals from the first of several single-turn diagnostic coils placed along the ferromagnetic element of a FMG.[13] As reported in Ref. 13, it was practically impossible to obtain clear electrical signals from diagnostic coils placed close to the impact face of the magnet.

In conclusion, we demonstrated that there is a heretofore unexplained type of gas breakdown that occurs in explosively driven electric generators and that the resulting plasma may be the cause of the development of gas discharge in these generators.

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