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Optical Diagnostics on Helical Flux Compression Generators

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Abstract—Explosively driven magnetic flux compression (MFC) has been object of research for more than three decades. Actual interest in the basic physical picture of flux compression has been heightened by a newly started Department of Defense (DoD) Multi-University Research Initiative. The emphasis is on helical flux compression generators comprising a hollow cylindrical metal liner filled with high explosives and at least one helical coil surrounding the liner. After the application of a seed current, magnetic flux is trapped and high current is generated by moving, i.e., expanding, the liner explosively along the winding of the helical coil. Several key factors involved in the temporal development can be addressed by optical diagnostics. 1) The uniformity of liner expansion is captured by framing camera photography and supplemented by laser illuminated high spatial and temporal resolution imaging. Also, X-ray flash photography is insensitive to possible image blur by shockwaves coming from the exploding liner. 2) The thermodynamic state of the shocked gas is assessed by spatially and temporally resolved emission spectroscopy. 3) The moving liner-coil contact point is a possible source of high electric losses and is preferentially monitored also by emission spectroscopy. Since optical access to the region between liner and coil is not always guaranteed, optical fibers can be used to extract light from the generator. The information so gained will give, together with detailed electrical diagnostics, more insight in the physical loss mechanisms involved in MFC.

Index Terms—Electroexplosive devices, explosive generators, optical diagnostic, optical imaging, optical spectroscopy, shock waves.

I. INTRODUCTION

THE EFFICIENCY of magnetic flux compression (MFC) generators is still limited to values of approximately 5%–30%, depending on the size or energy multiplication factor [1] of the particular generator. Several possible loss mechanisms have been discussed in the past [2], [3]. They include, for instance, skipping of helical turns, so-called clocking that may occur when the liner is slightly off-axis or the expansion is nonuniform. Losses connected with the liner-helix contact point seem to be most sensitive to arcing and ripples that are forming on the liner surface. The arcing will depend on the thermodynamic state of air or any other gas the generator

is filled with. It is known that shock waves with high Mach numbers generate high temperature and pressure with a fairly high ionization degree and conductivity [4].

The present investigation has been focused on the liner's expansion in air under atmospheric pressure and its possible impact on loss mechanisms. Though most of the experiments were carried out in air for making MFC generators more practical, some results have been gained with SF₆ as background gas. Mostly optical diagnostics, imaging and spectroscopy, have been used to assess the temporal development of liner expansion, liner–stator contact and thermodynamic state of shocked gas. Additionally, a simple resistivity experiment has been performed to link any change in resistivity with the optically observed phenomena.

II. EXPERIMENTAL SETUP

All explosive experiments were conducted inside an explosive chamber with about 1.5-m diameter; the employed diagnostic methods are shown schematically in Fig. 1. Optical access into the chamber was established by 200-mm diameter, 25-mm thick, Lexan viewports. Some of the viewports were equipped with 50-mm diameter Pyrex or Plexiglas inserts. The Pyrex and Plexiglas inserts were necessary due to the comparably inferior optical quality of Lexan. In particular, the Lexan would produce a disturbing stripe pattern in the high-speed laser photography. Lexan, however, exhibited the highest fracture toughness and a viewport made entirely of the insert materials would readily disintegrate due to the shock wave and impacting shrapnel.

The destructive force of an exploding copper liner—copper is often used as armor-piercing material—demanded also the almost exclusive use of aluminum as liner material for the sensitive optical diagnostic. The outer diameter for all liners was kept at 38.1 mm with 3- or 1-mm wall thickness. OFHC-T6 copper and 6061 aluminum was used either as received or annealed. The metal liners were filled with the high explosive (HE) composite C-4 by handpacking it. The HE was packed flush with the end of the metal liner, and it was set off by using Reynolds RP501 detonators, inserted about 10 mm into the HE from one end. For the investigation of the liner-helix contact point a Lexan tube, 70-mm inner diameter and 3-mm wall thickness, was centered around the metal liner. Both liner and tube had a length of 150 mm.

The upper limit for the speed encountered in these experiments is comparable to the detonation velocity of C-4, which is 8.37 mm/μs. About 0.1 mm can be reasonably resolved with optical diagnostic. This would demand a time resolution of better

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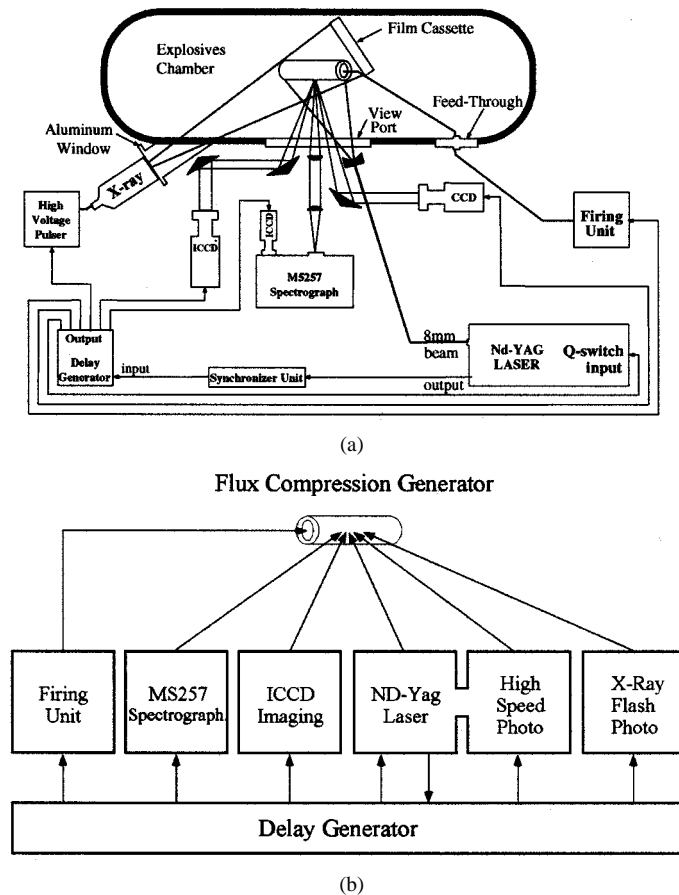


Fig. 1. (a) Sketch of the diagnostic setup physical layout. (b) Schematic setup of optical diagnostics. Laser is mastertrigger, trigger-sequence is from the left to the right.

than about 12 ns. However, as it will be discussed later, the liner material will move much slower at about 1–2 mm/ μ s, which would require a lower time resolution of 50–100 ns.

When the liner and tube are loaded, they are placed close to the center of the tank, allowing easy access for three optical diagnostic methods through the central viewport. X-ray flash photography is performed through a different port with the line of sight at an angle of about 40 degrees to the chamber main axis. It is unlikely that shrapnel directly hits the X-ray flash unit, so that a 6-mm thick aluminum window has been found sufficient to protect against the explosive shock wave. The X-ray film cassette is placed inside the explosive chamber. An aluminum/high-density foam sandwich protects it. In contrast to imaging techniques that work in the optical wavelength regime, the X-ray photography method is completely insensitive to interfering background radiation. Obviously, the objects under investigation generate no self-radiation in the X-ray regime. In addition, this method is also unique with respect to the ability to look inside an otherwise opaque object.

One intensified charge coupled device (ICCD, Ziener & Associates) takes an image of the liner illuminated by flashlamps [5] or of the self-emission. In both cases an exposure time of 14 ns was set, which freezes the liner expansion. The ICCD camera is approximately a factor 1000 times more sensitive than regular film. The second ICCD is used as the detector for the emission spectroscopy. It is flanged to the output of an

imaging spectrograph (Oriel, MS257), which enables obtaining spatially resolved spectra along a line. The spectral range captured in a single shot is variable from about 25 to 200 nm. The smaller spectral range has the benefit of a higher resolution, which is helpful when fine spectral details have to be resolved. A two-lens system is used to image the liner onto the spectrograph entrance slit. The magnification has been carefully chosen so that a line of about 60-mm length is captured by the ICCD-spectrograph system. A gate-time of 100 ns has been set throughout the experiments.

The final piece of diagnostic comprises a Nd-YAG laser (Spectra Physics) and a CCD that is used in open shutter mode. The laser is vertically polarized at an output wavelength of 532 nm and has 540-mJ output energy at a pulse width of 7 ns. A concave lens with focal length $f = -100$ mm widens the initially 8-mm beam so that approximately one half of the liner is exposed. A polarizer in front of the CCD blocks laserlight that gets directly reflected at the object without changing the polarization direction. In a similar way, ambient light or light from the explosion is blocked by a narrowband, ≈ 3 -nm bandwidth, laser linefilter.

As indicated in Fig. 1(b), the laser is also the master trigger for the entire experiment. In order to get maximum output pulse energy, the internal laser pump lamps have to run in a repetitive mode at 10-Hz. However, only a single laser pulse is actually fired during the experiment. A synchronizer unit lets only a single pulse of the 10-Hz pulse train pass to the delay generator, which sequentially triggers the HE firing unit, an adjustable time interval later the two ICCD cameras, 1 μ s later the laser Q-switch, and still 1 μ s later the X-ray flash unit. This approach ensures that no residual fluorescence of the laser or the X-ray flash distorts the imaging or emission spectroscopy results.

III. RESULTS AND DISCUSSION

The expansion of an annealed 6061-aluminum liner with 38.1-mm outer diameter and 3-mm wall thickness was measured with flashlamp illumination and 14-ns ICCD exposure time. At about 18 μ s after initiation of the blast, the cone-shaped armature expansion becomes visible. The detonation front moving at a speed of 8 mm/ μ s along the liner axis and the radial velocity of about 2 mm/ μ s cause the very typical shape, as it is depicted in Fig. 2. (Fig. 2 and all following images have been rotated by 90° for viewing purposes.) The explosive gases are visible as a jet streaming out the end of the bulb-shaped liner. A maximum expansion ratio at the largest bulb diameter of approximately 2.5 is detected. Additionally, the laser high-speed photography with its superior resolution revealed the start of liner breakup at an expansion ratio of less than two; visible dimples are being formed at this point, see Fig. 3. Fragmentation follows at an even later time.

The same general shape of the exploding liner becomes visible when solely the self-emission of the expanding liner is imaged with 14-ns exposure time, see the left half of Fig. 4. Shown in the right half is the spatially resolved emission spectrum (wavelength axis is from the left to the right), and its spatially integrated part, taken at the same time, $t = 18$ μ s. The spectrum, which is spatially (vertically) matched to the

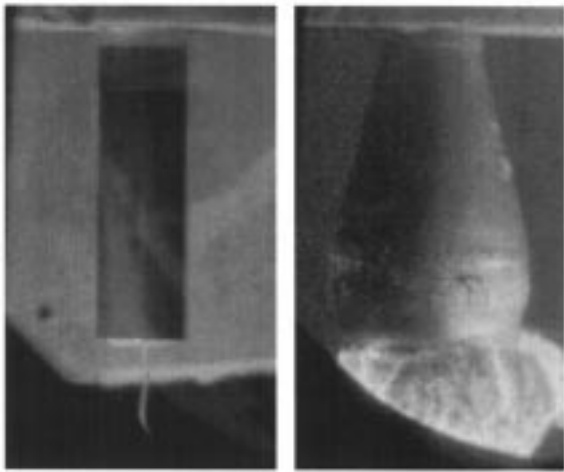


Fig. 2. Image of exploding aluminum liner with 3-mm wall and reference, illuminated with flashlamps. Detonator leads are visible in the reference picture. ICCD gate time was set to 14 ns. The bulb shape is due to the pressure loss at the open liner end. Expansion angle is about 15°.



Fig. 3. Laser high-speed photograph of an expanding 3-mm wall aluminum liner showing dimple formation starting at an expansion ratio of about 1.8. Image width is 10-mm. Dark areas in the upper two thirds of the photograph are due to the lasers imperfect spatial profile.

image, shows what appears as a single line but is the unresolved Na-doublet at 589 nm. The observed sodium is obviously a contamination from liner handling and processing.

The HE products, a gas mixture at high temperature, cause broad-band luminescence throughout the spectrum. This broad-band spectrum is visible as a bright ribbon in the lower portion of spectral image depicted in Fig. 4. The dark area between the explosive gases and a luminous ring on the liner can also be found in the spectrum. However, the origin of this dark area or this luminous ring has yet to be determined. Also, the sodium emission can hardly be matched with the emission visible in the left-hand image of Fig. 4. It is believed that most of this emission is broad-band and therefore does not show up as a distinct line in the spectrum. The bright spot at the right edge of the exploding liner is due to explosive

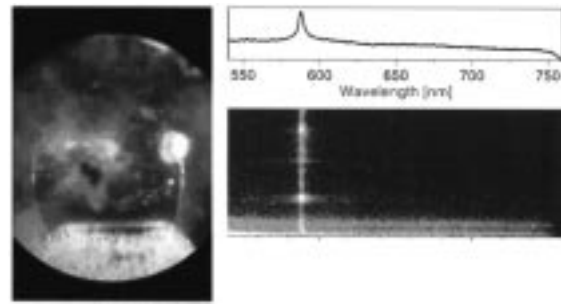


Fig. 4. Aluminum liner, 3-mm wall: self-emission captured with ICCD, 14-ns gate time and spectrograph-ICCD system, 100-ns gate time. Spectrum is vertically matched to image; the center of the exploding liner is imaged on the spectrograph entrance slit. Prominent line is Na I emission; the broad-band background is due to the emission from explosive gases.

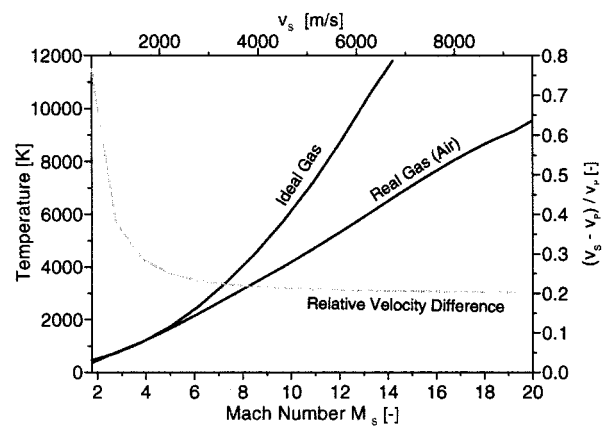


Fig. 5. Shockwave temperature dependence on receding shockwave velocity for ideal gas and air, assuming a normal shock. Index “s” designates shockwave properties, v_p is the speed of the pushing “piston.”

gas penetrating through the liner wall. The subsequent radiation is broad-band and is not detected as a single line in the spectrum. The same effect is believed to cause a reflection in Fig. 2, visible as a bulge, somewhat above the maximum diameter of the exploding liner. This was also concluded from the results of high-speed laser photography which is largely insensitive to any self-emission. Any cracks, ripples or holes in the annealed 3-mm wall aluminum liner were observed only beyond an expansion factor of approximately 1.8. An example of laser high-speed photography will be discussed later for an aluminum liner inside a Lexan tube, see Fig. 7.

Within the spectral range of the observed emission spectrum lies the strongest atomic nitrogen emission at $\lambda = 744$ nm. A normal shockwave in air at about 8 mm/ μ s, \approx detonation velocity, would result in a temperature of approximately 10 000 K, see Fig. 5, a pressure of 750 atm [4] and a atomic nitrogen molefraction of 0.5. That means a large fraction of the nitrogen in the air would have been dissociated. However, no atomic nitrogen line could be unambiguously identified for all measured emission spectra. Therefore, the nitrogen line intensity must be below the sensitivity limit of the detection system. In Fig. 6, a rough estimate of the counts expected to be measured by the ICCD-spectrograph system as a function of temperature is given. The estimate includes all system properties, such as the

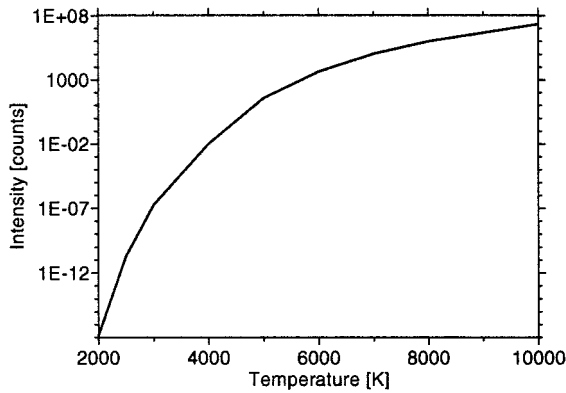


Fig. 6. Sensitivity analysis of atomic nitrogen emission ($\lambda = 744$ nm) for the spectrograph-ICCD system.

detected solid angle, the ICCD spectral sensitivity and gate time, and the spectrograph sensitivity. The detection limit is reached when the spatially integrated number of counts is below one hundred. There are 256 pixels in the spatial direction, which means that the detection limit is at about one count or 4500 K. When molefraction and physical density variation is included, the detection limit is found to be approximately 5500 K. This temperature is reached for a shock-wave Mach number, $M_S = 12$, see Fig. 5. The speed of the pushing solid material, v_P , is about 20% lower than the shockwave velocity; i.e., $v_P \approx 4.5$ mm/ μ s. The ICCD imaging method with a higher sensitivity than the ICCD-spectrograph system should be even more capable of detecting any shock coming off the liner. However, anything that would resemble the appearance of a shock-wave has not been observed throughout all conducted experiments. Therefore, X-ray flash photography, which is insensitive to possible distortions caused by shockwaves, did not produce any new results with regard to a uniform liner expansion. However, it might become more informative when assessing a complete generator.

The lack of an observed shock wave is not surprising when the deformation of the liner is more closely examined. It appears that the liner deforms due to a combination of a mainly radial movement and a stretching parallel to the liner surface [6], [7]. For an expansion angle of 15° , the radial velocity of a liner mass element is almost equal to the velocity normal to the liner surface. Any shock into the gas can effectively be transferred only by its normal component, which is here mainly determined by the radial velocity, $v_R \approx 2$ mm/ μ s. It translates for the thermodynamic state of the gas behind the shockwave to $M_S \approx 5$ and $T \approx 2000$ K, see Fig. 5.

This result is vital for any loss mechanism connected with electric breakdown. The ionization degree resulting from $T = 2000$ K is far lower than the one expected for a temperature of more than 10 000 K as it would follow from a shock at 8 mm/ μ s. Moreover, the relatively low gas temperature should allow detecting any breakdown or arcing inside a live MFC generator with emission spectroscopy with little background interference. The situation will be somewhat different when the liner's expansion is affected by a stator. Gas trapped near the liner-stator contact point might reach higher temperatures than 2000 K. This will be subject of future research.

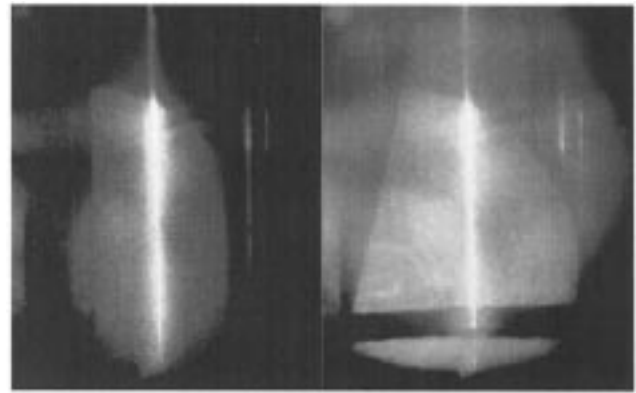


Fig. 7. Laser high-speed photography of aluminum liner in Lexan tube. Left image is reference. Dark ribbon at liner-tube contact is about 6-mm wide. Liner-tube contact occurs at an expansion ratio of 1.85.

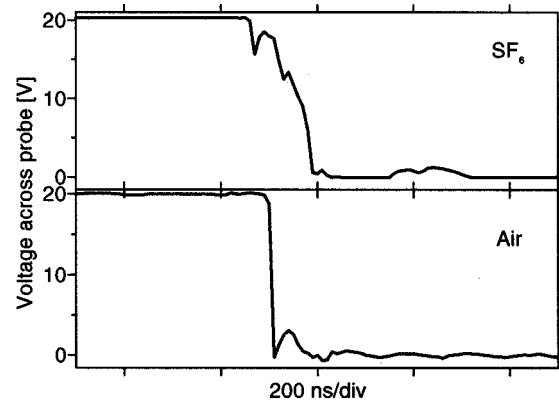


Fig. 8. Voltage across two bare wire probes inserted through insulating stator for gases air and SF_6 .

Utilizing high-speed laser photography, thus eliminating the self-emission of liner and Lexan tube, the liner-stator contact becomes visible as a black ribbon, see Fig. 7. The width of the ribbon is approximately 6 mm, which is about the projection of the expanding liner onto the stator wall. This includes the thinning of the liner to about 1.5-mm wall thickness at an expansion ratio of approximately 2. That means kinetic energy gets transferred from the liner to the stator within the width of the ribbon. The crushed stator material, Lexan, appears to be highly absorptive at the laser wavelength. Losses arising from a misaligned liner-stator configuration or a nonuniform explosion should be minimal since the ribbon is almost perfectly perpendicular to the liner.

The black ribbon itself lies within a range of bright self-emission, which is about twice as wide and which precedes the ribbon by approximately 5 mm. Though the origin of this emission is not completely understood yet, it seems to be connected with a drop in resistivity—either through the gas or through the stator—that also precedes the ribbon. The voltage measured across two bare wire probes, inserted through the insulating stator at the same longitudinal position, is depicted in Fig. 8. The separation between the wire probes was about 25 mm, the bare wire length about 10 mm. An early voltage drop is observed, about 50-ns wide, for air and SF_6 between liner and stator. The calculated resistance reaches a local minimum of 50

or 500 Ω , respectively. Although the voltage diagnostic was not completely impedance-matched, which limits the time resolution and causes some signal reflections, it is obvious that the resistance drops faster in air than in SF₆, where about 100 ns are needed to make full contact via current flow through the shocked gas and liner.

IV. SUMMARY

Several optical diagnostic methods were applied to evaluate the temporal and spatial behavior of explosively driven MFC generators. The focus has been on the uniformity of liner expansion, the thermodynamic state of the shocked gas, and the liner–stator contact point.

Annealed 6061-aluminum, 38.1-mm outer diameter, and 3-mm wall thickness, hand-packed with high explosive C-4 showed no visible cracks or dimples up to an expansion ratio of approximately 1.8. The temperature of the shocked air surrounding the freely expanding liner has been estimated to be below 5500 K, possibly as low as 2000 K. Using laser high-speed photography, the quality of the liner–stator contact has been assessed. The contact point could be identified as a sharply defined ribbon.

Ongoing and future research will shift focus to diagnostic on complete or live MFC generators.

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