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AUTHOR(S) K. D. Ware and C. R. Jones

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Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

Optical emission of exploding-film and wire-initiated discharges

K. D. Ware and C. R. Jones

University of California, Los Alamos National Laboratory, Chemistry Division
P. O. Box 1663, Los Alamos, New Mexico 87545Abstract

Optical sources of several megawatts-cm⁻² over large surface areas are available from electrical discharges initiated by exploding films and wires immersed in a gas. Discharging high-current capacitor banks into the metal conductors causes them to melt, vaporize, and then eventually ionize to a high-conductivity plasma of less than a milliohm/cm-length resistance. As such, over 1,000 MW of ohmic heating goes into the discharge, elevating its blackbody temperature up to 35,000 K.

In this work, film thicknesses from 0.1 to 10 μ m and wire diameters from 0.051 to 0.25 mm with lengths ranging from 8 to 90 cm were exploded and the brightness temperatures measured in the spectral regions about 200, 280, and 520 nm. The optical emission generally increased with the time rate of change of the current, the current per unit diameter for the films, and the gas pressure in the cell, but showed little dependence on the mass or kind of metal exploded. The discharge radius expanded at velocities of approximately 1.5 km-s⁻¹.

Introduction

The phenomenon of exploding metal conductors in electrical circuits began over two hundred years ago as a demonstration of the continuity of current flow.¹ Exploding wires became a subject of much scientific interest beginning about 1950 and the published literature is both diversified in scope and voluminous in reported experiments.²⁻⁵ Exploding metal films and foils have a less rich history, perhaps beginning in the early 1960s. However, one thing clearly emerges from studying the experimental results as reported over the past 30 years; the phenomenon of electrically exploding metals as wires, films or foils is a copious source of physical processes, the selected occurrences of which depend on the history and properties of the metal, the environment, and all the electrical circuit characteristics involved. The electrical power source is particularly important in the specific observables of the phenomenon. Therefore, any attempt to describe broad-brush what happens when an electrical current passes through a conductor with sufficient energy deposition to explode the conductor would be foolhardy for the needs of this paper. It suffices here to simply say that the metal heats up, goes through phase changes to a liquid and a gas rapidly enough that it is basically inertially confined. At this point, exploding wires often become very resistive and the current is limited to a relatively low value. This period of low conductivity, the so-called "dwell time," can be so momentary as to appear to not occur at all which is the usual case with exploding films, or it can extend for tens of microseconds. Expansion eventually increases the mean free path for the electrons enough to cause impact ionization and avalanching. The current in this "restrike" can then rise rapidly as controlled by the circuit elements and the dynamics of the electrical discharge. The electrical power flow into the plasma column is generally of such a magnitude that the plasma temperature must be elevated to a very high value, tens of kilodegrees kelvin, in order to dissipate the energy. These exploded metal initiated discharges in atmospheric pressure conditions generally show an approximate blackbody radiation spectrum.

Load characteristics

Figure 1 is a photographic view of one of the discharge chambers used in this study. In operation the chamber would have 8-coaxial cables (not shown) connected across the kynar insulator section of the chamber (near-end in figure) for delivering the power from the capacitor bank. The films and wires are supported along the axis of the 20-cm-inner diameter chamber for lengths up to 90 cm. A shorter chamber was used for most of the study with shorter films/wires. The two side ports on the chamber were used to observe the radial expansion of the axial discharge with a streak camera and the spectral emission with three photodiodes. This chamber was used with 25-cm-diam optics on the ends as a molecular and atomic iodine laser.⁶

The impedance characteristics of an exploding wire or film load depend on the power source and the electrical circuit as a whole unit. It is, therefore, important here to describe the electrical circuit involved in the reported impedance characteristics. Figure 2 shows the basic electrical circuit used in many experiments to explode metal wires

Figure 1. Discharge chamber used for exploding films/wires.

Figure 2. Electrical circuit.

Figure 3. Current and voltage traces for an exploding film.

and films. In addition to the usual elements of initial capacitance, C , charged to a voltage V_0 , the total initial tank inductance L_0 and the switch S_w , the exploding wire or film adds a time-varying inductance $L(t)$ as well as a time-varying resistance $R(t)$. It should be noted that an exploding axial wire discharge will expand radially outward which is against the self-magnetic field and thereby reduces the total circuit inductance unless the self-magnetic forces exceed the plasma pressure. A film or foil, on the other hand, can be designed to thermally expand against or with the magnetic pressure by returning the current outside or inside the cylindrical discharge, respectively.

In Fig. 3 is shown a typical current and voltage trace for a $40 \mu\text{F}$ capacitor bank charged to 47 kV (45 kJ) and discharged through a $1\text{-}\mu\text{m}$ thick aluminum film deposited on a 1.3-cm -diam Lucite tube, 34-cm long. There were $1.47 \mu\text{H}$ of initial total circuit inductance. The voltage probe was located across the discharge chamber where the coaxial cables were connected.

The initial resistance of the 0.1-mm tungsten wire was 2.5 Ω and of the 1- μ m aluminum film was 0.4 Ω . These cold resistances probably increased substantially during the first few microseconds after switch closure as the metal temperature rose and began to liquefy and vaporize. The current may nearly turn off during this phase and go through a restrike before substantial current flows again. At this point in time the resistances drop dramatically and at peak current time or $I = 0$ was 29 m Ω for the wire-initiated discharge and 31 m Ω for the film-initiated discharge. At the same time the IR voltage drop was 5.5 kV or 162 V/cm for the wire discharge and 5.9 kV or 174 V/cm for the film discharge, respectively. Approximately 40% of the initially stored electrical energy, $CV^2/2$, went into plasma heating by the first zero current time of $\sim 27 \mu$ s, for both the wire and the film.

For the simple circuit discussed above nearly all the stored energy ($CV^2/2$) must go into the ohmic heat eventually. However, to first approximation it is the power input which is in equilibrium with the radiative power output, P_R . The radiative power output for a blackbody is related to the temperature by

$$P_R (\text{watt}) = \sigma T^4 A$$

where $\sigma = 5.66 \times 10^{-12} \text{ W/cm}^2\text{-K}^4$, A is the radiating surface area and T is the blackbody temperature. The peak power into ohmic heating for the exploding wire was 1.13 kW and for the exploding film was 1.16 kW which occurred at about 10 μ s. These discharges have been measured to expand radially at a near constant rate of 1.5 km/sec. Therefore after 10 μ s the 34-cm long exploding wire would have 320 cm^2 of surface area and the film (starting at 1.3-cm diameter) would have 460 cm^2 of surface area. If the ohmic power input was in equilibrium with the radiative power output then the blackbody temperatures for the wire and film initiated discharges would be 28,100 K and 25,000 K, respectively. These calculated equilibrium temperatures are in reasonable agreement with the measured brightness temperatures, discussed at length in the following section, measured in the uv spectral range to be 32,000 K and 23,000 K for the wire and film initiated discharges, respectively.

Optical source scaling laws

The purpose of this section is to describe and discuss in some detail the emission characteristics of the exploding metal wires/films and how this optical source scales with the controllable circuit/discharge parameters. Simplistically we would just like to know the spectral radiance, in $\text{W/cm}^2\text{-nm-sr}$, from a specified exploding metal conductor with a certain time history of current and in a given discharge environment. Our principal observable will be the spectral irradiance at three photodiodes filtered to record optical irradiance around 200, 280, and 520 nm. The choice of the first two wavelengths was based in part on their usefulness in pumping molecular iodine (342 nm) and atomic iodine (1.31 μ m) lasers, respectively.

In Fig. 4 are three photodiode signal traces at the three wavelengths indicated and the exploding film shown in Fig. 3. The traces are basically alike yet contain differences in

Figure 4 Photodiode traces for an exploding film, indicating the brightness temperature corresponding to each peak.

details. For example, the 200-nm radiance at first appears to rise faster than the other two wavelengths, whereas the brightness temperatures rise at very similar rates during the first 1 or 2 μ s up to about 15,000 K and then a loss effect begins reducing the 200 nm further increase in brightness. Actually all these brightness temperature traces show a strong loss term other than σT^4 because the ohmic heating power going into the plasma reaches a maximum just before the peak current or around 10 μ s in this example. These loss effects were not examined but they could be due to cold gas being swept up by the expanding plasma or even phenomena like stimulated absorption especially for the 200 nm radiation. All three traces approach 13,000 to 14,000 K after 30 μ s.

We will be spending very little time in the remainder of this section discussing the temporal behavior of these brightness temperature measurements. Instead, we will be recording the peak value of $T_b(t)$ to discuss the dependence on various controllable system parameters. This criterion itself is questionable because as mentioned the three $T_b(t)$ do not all reach their maximum value at the same time and furthermore the temporal traces themselves change shape under different conditions. For most of the irradiance measurements the photodiodes were placed 2 m from a 3-mm-diameter aperture which was 14 cm radially from the exploding wire/film axis. The photodiodes were individually calibrated using standard sources and have an absolute-value confidence level far better than the measured signal uncertainty.

In the following discussion we will be describing data from exploding 0.1-mm-diameter tungsten wires or 1.3-cm-diameter, 1- μ m-thick aluminum films on an acrylic resin substrate with a maximum capacitor bank source of 40- μ F charged to 47 kV. This circuit tends to be fairly inductive, of the order of a microhenry, and as such the half-cycle times were around 25 μ s. (See Fig. 3.)

The variation of the brightness temperatures versus the discharge gas pressure was measured at a fraction of an atmospheric pressure up to 4 atm. For the exploding wire in SF_6 the variation of the brightness temperature at 280 nm was small with a very broad maximum at ~2 atm. We found similar results with the exploding films with SF_6 and CF_4 but found that with Ar (100 torr of SF_6 added for electrical discharge reasons) the temperature continued to increase even up to 4.0 atm. Figure 5, shows these later variations with pressure for the 200 nm emission with the exploding film.

Figure 5. Radiance at 200 nm from an exploding film versus the background gas type and pressure.

To discuss the dependence of the discharge temperature on the source energy or even the charge voltage is not simple except to say categorically that it increases approximately with source energy. However, as we discussed in an earlier section it is how the energy is

Figure 6. Irradiance and brightness temperature at 280 nm versus discharge length.

delivered to the load or the source-to-load impedance match that is important. Clearly, for more energy input or perhaps more specifically more input power per unit mass of the discharge the higher the equilibrium blackbody radiation temperature. Lengthening the wire or film will lower the temperature for a fixed input power. However, both these dimensional changes could make a favorable impedance match change and actually increase the power input enough to override the physical mass change of the discharge. Figure 6 shows some photodiode signals and indicated brightness temperatures at 280 nm versus the discharge length. The data in the lower left hand side of the figure were with the aluminum film and show only ~10% reduction in the photodiode signal for a factor of 4 increase in the discharge length. This simply means that the efficiency of power transfer increased almost linearly with the film length. Clearly this could not continue to much greater lengths since over 40% of the bank energy is going into the film during the first half-cycle for the 34-cm length. The data for the exploding wire more clearly shows the nearly linear decrease of photodiode signal (irradiance) with wire length, that is, constant efficiency.

We have noted two important parameters for optical emission from exploded metal conductor discharges which are the initial time-rate-of-change in the current and the specific current per circumference of the films. Figure 7 shows both 280 and 520 nm emission versus the initial time-rate-of-change in current, $\dot{I}_0$ going into the 1.3- μ m diameter aluminum films. First we must note that the nine data points shown represent nine different capacitor bank conditions of 10, 20, and 40 μ F with 27, 37, and 48 kV for over a factor of 12 in energy range. The straight lines passing through the data and the origin are not necessarily the "best fit" but simply illustrate a fairly strong linear dependence of the exploding film spectral irradiance on $\dot{I}_0$.

In Fig. 8 have been plotted a number of brightness temperature measurements $T_b(t)$ for various exploding aluminum films and foils versus the specific current $J(t)$, which is the discharge current $I(t)$ normalized by the circumference of the expanding discharge. The nine data points indicated by $\circ$ -, $\diamond$ -, and $\pm$ - were taken with the capacitor bank and with 1- μ m thick, 34-cm long Al films deposited on acrylic resin substrates ranging from 2

Figure 7. Spectral emission at 280 and 520 nm versus the initial time-rate-change in current for the exploding films.

to 16-cm in initial circumference, as indicated in the figure. The broken line with arrowheads near these other data points is the full time history of $T_{280}(t)$ versus $J(t)$ for the discharge shown in Fig. 3 and 4 during the first current half cycle. The behavior is very linear up to the peak current but then as the current comes down on the second quarter cycle we see the temperature holding up at 14,000 K at the first current zero. We can also see in the figure a broken-curve which is the time history from 1 to 12 μ s of $T_1(t)$ versus $J(t)$ for an exploding 100- μ m diameter wire initiated discharge, assuming a constant, linear expansion rate of 1.5 km/s for the current sheath. The latter data appears to represent the same linear dependence on $J(t)$ as the various small diameter film discharges. It is not clear at this time just how this apparent linear increase in the brightness temperature versus the specific current is supported theoretically.

The squares ($\square$ - and $\blacksquare$ -) in Fig. 8 were taken with a larger capacitor bank using 32-cm circumference 1- μ m thick Al films and the Russian data indicated by the "band" were for 20- μ m Al free-standing foils of 57-cm circumference. The agreement between these larger diameter discharges is very good. Some of our data, $\square$ -, connected by a broken line is actually the time history of the T_1 versus J which seem to follow the same variation as the individual peak values from each discharge. The power into ohmic heating is simply

$$P_R = VI.$$

If this is in equilibrium with the blackbody radiate power out, $\sigma T^4 A$, then

$$VI = \sigma T^4 A.$$

Then noting that the voltage drop per unit length of film at peak current time, $i = 0$, was a constant independent of the peak current value or the initial film length then

$$T \propto J^{1/4}.$$

Figure 8. Brightness temperature measurement versus the specific discharge current for several different exploded metal conductor initiated discharges.

The large diameter data in Fig. 8 varies between $J^{1/4}$ and $J^{1/3}$ in reasonable agreement with the simple power equilibrium argument.

The data in Fig. 8 appear to show two different dependences on J . We believe that the difference is partially related to the quarter period time of the capacitor banks. Recall from Fig. 7 that the spectral radiance depends nearly linearly on the initial time-rate-of-change in current, i_0 . Also during early time in the discharge the resistance is very large and decays to a few milliohms per centimeter length after about $10 \mu s$. For the fast capacitor banks the current is approaching its maximum on this time scale. Whereas for the larger films/foils and slower capacitor banks the resistance starts lower and has dropped to its relatively low nearly constant level early in the quarter period and is approaching an equilibrium state by the quarter period time. In other words we are suggesting here that higher brightness temperature responses are due in part to a non-equilibrium superheating phenomenon early in the breakdown stages which averages out for the larger films/foils and slower banks so they demonstrate more of the power equilibrium.

We have used different thicknesses and metals as the exploding films and even though the results are sketchy we can make some general comments. Little variation was found in the radiation or electrical behavior among aluminum films from $0.5\text{-}\mu m$ up to $10\text{-}\mu m$ thick. Brightness temperatures measured from exploding $1\text{-}\mu m$ films, 1.3-cm diameter, 34-cm long using copper, aluminum, nickel, and tungsten showed Al to be slightly better than the other three metals at all three wavelengths.

Conclusions

We have found that the exploding film and wire initiated discharges are very bright optical sources and that they can be fairly efficient with proper attention to the electrical circuit. However, the fraction of radiation in the near-uv region decreases with

the blackbody temperature at these high temperatures and is only 5% for a 50-nm band around 270 nm at 30,000 K. Therefore, we may want to look for ways to enhance the wanted spectral region through nonequilibrium or spectral conversion techniques for more efficient laser pumping.

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