Breakdown patterns in Branly’s coheror

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We use thermal imaging of Joule heating to see for the first time electrical conducting paths created by the so-called Branly effect in a two-dimensional metallic granular medium (aluminium). Multiple breakdowns are shown to occur when the medium is submitted to high voltage increases (more than 500 V) with rise times close to one hundred of microseconds.

I. INTRODUCTION

In 1890 Edouard Branly reported a surprising property of certain metal powders: when a radio source is approached to a generally non-conducting assembly of iron or aluminum grains, the assembly becomes conductive, and remains conductive even after the source is removed. A similar phenomenon may occur if the metal powder is submitted to a DC voltage: as soon as the voltage exceeds a certain threshold level, the assembly becomes conductive and remains so when the voltage is removed or reduced. The process is not however entirely irreversible; a small (mechanical) shock is sufficient to turn the assembly back to its original, insulating state. The radio-induced conductivity of this set-up (also called Branly’s coheror) was used in the first wireless telegraph receivers.

Despite the recent development of physics of granular media, the behavior of Branly’s coheror is not completely elucidated. Several problems are indeed involved: the description of metallic electrical contacts (surface roughness, oxide layer), the distribution of local stress in a granular medium and the propagation of electromagnetic waves through a granular medium in the case of the radio induced conductivity.

Although a complete physical understanding of the phenomenon is to be found, some elements of information have been firmly established: without any oxide layer at the grains’ surface, this effect does not exist; a graphite powder, a precious metal powder, an aluminium powder previously reduced with hydrogen all directly conduct; 1/f noise and giant fluctuations of current are clear precursory to the transition to the conductive state; the conduction seems to be due to filaments of grains linked together (maybe by microfusions). This last point was illustrated by an experiment at the Palais de la découverte in Paris. The latter consisted of putting a point electrode in a metallic cup filled with grains, the filings became conductive when the voltage applied between the electrode and the cup was high enough. Then lifting up slightly the electrode, it was possible to pull up a chain of grains linked together.

In the following we present a visualization of the Branly effect (section 2). This method is used in section 3 to study the breakdown patterns occurring in a two-dimensional metallic granular medium when the latter is submitted to a high-voltage increase of varying rise time. The results are then discussed in section 4.

II. THERMAL IMAGING: A VISUALIZATION METHOD OF TWO-DIMENSIONAL BRANLY’S COHEROR

A. Principle

Up to now, no direct visualization of the phenomenon has been achieved. Connections between grains in the assembly are very tenuous and thus as one tries to extract the filament of connected grains, most probably the structure will be broken. Searching for links in an assembly of grains is not easy and not all links have to be part of a conductive path. Moreover the mechanical cohesion between grains is extremely small. Infrared imaging provides a solution to this problem: if a conductive path exists, there are energy losses in contacts by Joule heating and thus elevation of temperature. Even if the metal generally poorly emits in the mid IR, the oxide layer makes the grains emitting. When a current flows through the grains, the local heating generates an infra-red image of the conductive
path(s) provided that the assembly of grains remains two-dimensional. We performed many experiments in order to study the influence of different experimental parameters on the structure and the position of the paths.

**B. Realization**

We have deposited one monolayer of aluminium grains (diameter 400-500 µm) in a 20 mm square milled depression made in a thick disc of plexiglass and bounded by two flat copper electrodes. The layer of grains and the flat electrodes have been covered by a 40 mm diameter circular sapphire window (which transmits both visible and mid IR light below 5 µm). As it can be seen on figure 1, the set-up is maintained with a rubber O-ring screwed to the lower part.

![FIG. 1. Experimental set-up](image)

The conductive state is created with a high voltage generator (up to 1500 V) which can not deliver current through low resistances such as those obtained in the medium in its conductive state. We use a low voltage generator for the visualization. The latter is done with an IR camera 128 × 128 (AMBER 4128, InSb detectors with a cut-off at 6.5 µm) which allows us in the configuration used to reach a resolution of 200 µm by pixel. Between two consecutive visualizations, we apply mechanical shocks to the set-up in order to break the links previously created between the grains. Although not quantitative, the latter process was checked not to induce correlations in breakdown patterns, what suggests that most connections between grains are broken.

**III. SIMPLE AND MULTIPLE BREAKDOWNS**

The system of about 2000 aluminium grains we have used is sufficient to recover the main features described by Branly at the end of the last century. Although the two copper electrodes are only separated by a few tens of grains, an electrical impedance measure of the system in its original state gave us $R = 25 \text{ MΩ}$ and $C = 0.5 \text{ pF}$. After imposing a DC voltage of about 500 V, this resistance generally decreases down to about 100 Ω. When a current of a few mA flows through the coheror in this conducting state it becomes possible to see a conducting path (see figure 2). These images have been obtained by subtracting the background (i.e. the image of the same system when no current flows through). The orientation of the cell is the same as in figure 1. The two vertical black bands on the left and right sides correspond thus to the electrodes. The conducting path appears as a bright curve connecting both electrodes. One can clearly see intensity contrasts inside each path. As the current is imposed, these intensity contrasts are due to the resistance contrasts that exist between the different bonds linking the grains of the path. The brightest spots correspond thus to the most brittle bonds.

Beyond the simple visualization, this experiment allowed us to confirm the great dependence of the Branly effect on the stress distribution in the granular medium. The latter is indeed known to be very inhomogeneous [9], which should affect the quality of the electrical contacts. The specific case of spheroidal particles covered by a soft shell - typically an oxide layer - while the inside is rigid was recently studied by de Gennes [10] and could be very well adapted to the study of the Branly effect.
FIG. 2. Electrical conduction paths in a two-dimensional system of aluminium grains. The visualization is achieved with an infrared camera. The background has been subtracted so that the vertical black bands on left and right sides correspond to the copper electrodes.

FIG. 3. “Branly paths” created with a maximum voltage of 500 V and a rise time of about 100 µs.
Varying the position of the layer of aluminium grains, we have thus noted that in case of vertical position, the conducting path was almost always created in the lower part while it was spatially uniformly distributed in case of horizontal position. The very low stress induced by the weight of the upper grains suffices to change dramatically the electrical contacts distribution in the medium and the creation of the conducting path.

The efficiency of this visualization technique being established, we have then specifically studied the morphology of the conduction paths induced by a DC voltage increase of varying rise time and maximum voltage. The set-up consisted of a direct commutation limited by a resistor-capacitor \((R_0C_0)\) in series. The capacitance of the coheror in its non-conducting state being measured to be \(C \simeq 0.5\) pF therefore we have used capacitances greater than \(C\) to impose the rise time. We have varied the maximum voltage from 300 V up to 1500 V and the rise time \(\tau = R_0C_0\) from 5 \(\mu\)s up to about 100 ms. For each \((\tau, V_{max})\) point, we have performed 10 experiments.

The major results are the following ones:

- No path is created for maximum voltage values below a threshold \(V_c \simeq 500 V\). The coheror remains in its insulating state. \(V_c\) does apparently not depend on the rise time.

- Both slow \((\tau > 300 \mu s)\) and fast \((\tau < 30 \mu s)\) voltage rises lead to the creation of one simple unique conducting path (in a similar fashion as these shown on figure 2).

- For intermediate rise time \((30 \mu s \leq \tau \leq 300 \mu s)\), we generally see one simple conducting path but we frequently obtain (in a few tens of percents of the cases) complex paths with loops or branches and also non connected paths (see examples of such paths on figure 3).

The probability of having complex conduction paths is plotted versus the rise time of the voltage increase on figure 4. This figure has been obtained by averaging for each rise time the results of observations of all experiments made with a maximum voltage higher than 500 V. The behaviour of the coheror when applying a voltage increase is reported in the “phase diagram” of the figure 5.

**IV. DISCUSSION**

These preliminary results have obviously to be confirmed. The observation of two different “phases” is not completely surprising. One could have expected however to keep complex paths for very short rise times. Let us recall however that the system that we have studied is quite small. It only holds 40×40 grains, which corresponds to a few pixels by grain with the 128×128 we have used. It would be naturally interesting to test larger systems. Increasing the size of the system is however quite difficult in this configuration. The separation between single and multiple
paths can also be difficult because of the presence of little loops. The latter become undetectable when the resolution decreases.

![Phase Diagram of the Branly Effect](image)

**FIG. 5.** “Phase diagram” of the Branly effect. The x-axis corresponds to the rise time of the voltage increase applied to the coheror. The y-axis corresponds to the maximum voltage used. In area 0 ($V_{\text{max}} < 500\,\text{V}$) no conducting path is created, in area I ($V_{\text{max}} > 500\,\text{V}$ and $\tau < 30\,\mu\text{s}$ or $\tau > 300\,\mu\text{s}$) only one single path is created and in area II ($V_{\text{max}} > 500\,\text{V}$ and $30\,\mu\text{s} \leq \tau \leq 300\,\mu\text{s}$) the path(s) created can be either single or complex with loops, branches...

The possibility of a visualization technique should allow new developments in the study of this original phenomenon. One may first use it for constructing a realistic model. The main result of this first work is the occurrence of multiple breakdowns. This point could be a very interesting test for a future model. According to G. Kamarinos et al., the generation of paths is due to a succession of local dielectric breakdowns of the oxide layers (about 100 nm thick in case of native aluminium). This theory suggests a model for the medium as a simple network of resistor/capacitors. Individual breakdowns would then occur when the local voltage reaches a threshold level. If it can reproduce multiple breakdowns, such a model should allow to relate the characteristic values of the individual contacts with the critical rise time(s) for which multiple breakdowns occur.

One can also think to further improvements of the visualization technique. We have used here a DC voltage that allows us to see the conducting path. If we use a sufficiently high frequency AC voltage, one may hope to short-circuit some open contacts and also to visualize dead ends (if some are present in the system).

This work has been devoted to the study of the insulator/conductor transition of a metallic granular medium when the latter is submitted to a DC voltage. As noticed by Branly, such a transition occurs not only when a high DC voltage is applied to the system (this specific point was already described by Calzecchi-Onesti in 1884) but also at the reception of a radio signal (that was the major contribution of Branly since it permitted the realization of the first wireless telegraph receivers). A natural extension of the visualization work that we have described in this paper is thus to study this surprising property. On may especially try to compare the breakdown patterns obtained in the two configurations allowing to create a conducting path through the granular medium.

Other studies may concern the influence of mechanical stress on the conduction of a metallic granular medium. But beyond further studies about the Branly effect, one can also think of using infrared radiometry to visualize the mechanical stress distribution in two-dimensional metallic granular medium since the paths of maximum stress are also the most conductive.

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