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Why do aged fluorescent tubes flicker?

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Abstract

Our everyday experience of aged and defective fluorescent tubes or bulbs informs us that they may flicker and emit a clicking sound while struggling to light up. In this article, the physical mechanisms controlling the initial illumination of a functioning fluorescent tube are investigated using a simple and affordable experimental setup. Thermionic emission from the electrodes of the tube controls the startup of fluorescent tubes. The origin of the faulty startup of aged fluorescent tubes is discussed and flickering regimes using functional tubes are artificially produced using a dedicated setup that decreases electron emission by the thermionic effect in a controlled manner. The physical parameters controlling the occurrence of flickering light are discussed, and their temporal statistics are reported.

Keywords: plasma physics, electrodynamics, statistical physics

(Some figures may appear in colour only in the online journal)

1. Introduction

1.1. Physical phenomenon and article outline

Fascinating phenomena may emerge from the interplay between electromagnetism, fluid dynamics and quantum physics in plasma physics. Several experimental devices have recently been designed as educational tools at the undergraduate level [1–7]. Widely used, fluorescent tubes or other plasma-based lighting devices remain an affordable and simple way to introduce several fundamental concepts of plasma physics [8–12]. In this article, we analyse the startup of fluorescent tubes with an emphasis on the physical understanding of the flickering operation encountered during the startup of aged or faulty fluorescent tubes.

A basic description of how fluorescent tubes operate can be found in [13, 14]. Fluorescent tubes are long glass tubes filled with noble gas (usually argon) at low pressure (around

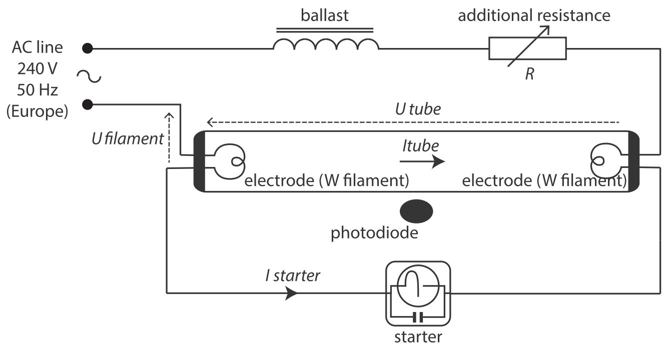

Figure 1. Schematics of the experimental setup.

100 Pa). When a plasma is sustained between the electrodes at each end of the tube, UV radiation from the plasma is absorbed by fluorescent coating within the glass tube, which re-emits white light.

Igniting and sustaining the plasma in the tube, while the electrodes are fed by electric power, requires external components—in particular, a ballast used to limit the plasma current and a system to aid ignition, known as the 'starter'. This article focuses on the simple configuration involving a magnetic ballast and a starter, as shown in figure 1. The electrodes (enclosed in the tube) are small foiled-tungsten filaments coated with a thin layer of highly emissive oxides in order to increase electron emission via the thermionic effect. The starter consists of a separate element in which a bimetallic strip is enclosed in a low-pressure noble gas capsule. When a voltage of the order of a few hundred volts is applied across the starter, the gas it contains is ionized. The bimetallic strip heats up due to ionic bombardment on each side of the strip, which acts as the electrodes of the starter plasma, and then deforms and closes the circuit. As a consequence, a large current (around 1 A) flows through the electrodes of the tube, which are heated up by the Joule effect. As no plasma is sustained in the (now-closed) starter, the bimetallic strip cools down and eventually opens up (Joule heating in the starter is negligible as compared to the heating due to plasma bombardment). This sudden current interruption induces a large over-voltage across the large inductance of the magnetic ballast, which allows the system to reach the breakdown voltage of the noble gas enclosed in the fluorescent tube and to sustain a plasma within the tube. In this article, we suggest that the startup of the functional tubes is controlled by the intensity of thermionic emission from the filaments. The steady-state operation of fluorescent tubes fed by the mains (240 V, 50 Hz in Europe, Africa or Asia or 120 V, 60 Hz in the USA) involves shimmering at twice the AC line frequency [15] (100 Hz in the work reported in this article). Fluctuations in light emission of the light source at the mains frequency (or its harmonics) has been studied in several contexts [16, 17]. Fluorescent tubes are based on the glow discharge of plasma, which is known (from back in the early years of plasma physics) to be strongly intermittent [18, 19], inducing intermittent light emission. On the other hand, fluctuations of the light emission of fluorescent tubes may also originate from moving non-linear potential structures in the plasma [20]. However, to the best of our knowledge, the defective startup of aged fluorescent tubes has not been reported elsewhere.

This defective startup, resulting in flickering light emission and pulses of sound emission is a widely observed phenomenon when the tube struggles to light up. The flickering light emission appears to be random in time with bursts of emitted light typically separated by a duration ranging from a few tenths of a second to a few seconds. As no steady-state regime is reached, the starter continuously switches between the open and closed states, leading to the typical clicking sound (synchronized with the flickering light emission of the tube). This peculiar regime is studied in detail in this article, introducing an experimental method which reduces the efficiency of the thermionic emission. This is achieved by lowering the temperature of the filaments of functional tubes when adding additional resistance to the electrical circuit. The article is organized as follows. Plasma breakdown, plasma *I–V* characteristics of the glow discharge and a detailed analysis of the normal startup are described in section 2. Section 3 then introduces an experimental setup that simulates the defective startup of fluorescent tubes resulting in random flickering light emission. The physical origin of this regime is then analysed and the statistics of the flickers are detailed. Concluding remarks are then provided in section 4.

1.2. What students can learn from this problem

The work presented in this article was done in preparation for the International Physicists' Tournament (http://iptnet.info), a worldwide competition for undergraduate students. Unlike a typical physics exam, the problems must not only be presented, but also challenged and reviewed by the other participants, allowing students to assume the roles of researchers, referees and editors, respectively. In addition to the challenge that the tournament presents, it provides students with an exciting and eye-opening experience in which they learn how to design experiments with the aim of solving physics problems, and how to constructively criticize scientific solutions. This article reports some of the results obtained from a series of six 4 h-long labs, where students solved the question of the origin of the flickers through problem-based learning.

The investigation of the dynamics of fluorescent tubes is a simple hands-on experiment used for the introduction of plasma physics at the advanced undergraduate level. A basic understanding of electrokinetic and electromagnetism concepts and experimental techniques is required to carry this study out. Basic concepts of plasma physics, such as gas discharge ignition and sustainment, can be experimentally introduced. Other advanced concepts, such as the thermionic effect, can also be grasped using this simple experiment. This includes the investigation of the effect of temperature on the resistance and electron emissivity of a filament. This article also provides an introduction to the statistical analysis of long time series and rare events.

2. Normal operation of the fluorescent tube

2.1. Characterization of the fluorescent tube plasma

Experiments were carried out using Philips TL-D 18 W commercial T8-type fluorescent tubes (26 mm in diameter and 590 mm in length) powered from the mains ($U_{\mathrm{mains,rms}} = 240$ V and $f_{\mathrm{mains}} = 50$ Hz) through a magnetic ballast (Mazda 36N20-01), as shown in figure 1. A Sylvania FS11 starter primes the tubes at startup. Current and voltage were measured using current sensors and differential voltage sensors, respectively, and the intensity of light emitted by the tube was measured using a Thorlabs PDA10A-EC photodiode. In the remainder of section 2, we investigate the normal startup operation described in the introduction. Note that the additional resistance displayed in figure 1 is introduced to simulate flickers (see section 3) and was set to $R = 0\,\Omega$ for the results presented in section 2.

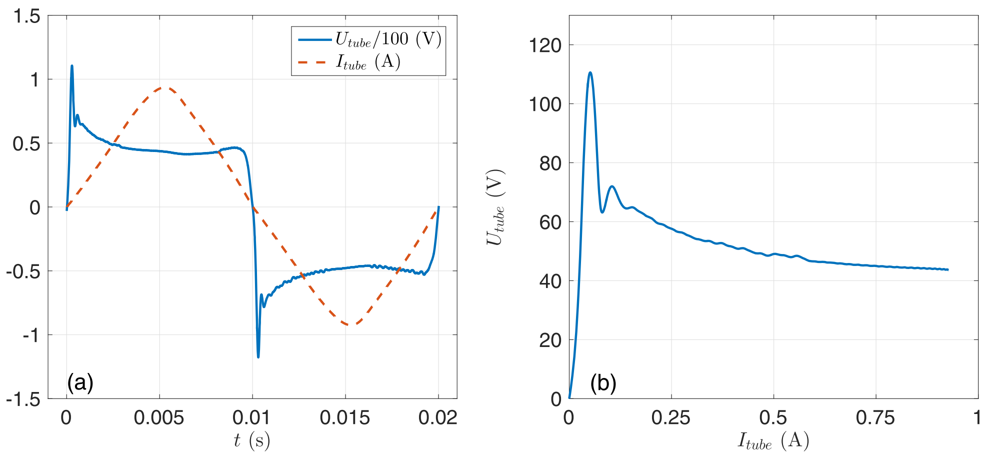

Figure 2. (a) Temporal evolution of I_{tube} and U_{tube} during normal operation for one 50 Hz cycle. (b) I—V characteristics.

2.1.1. I–V characteristic of the fluorescent tube plasma. Typical time series of the voltage U_{tube} and current I_{tube} across the tube during its normal steady-state operation are displayed in figure 2(a) over 20 ms. The $I - V$ characteristic shown in figure 2(b) was extracted from these time series and is typical of the glow discharges of plasma [21], with a local negative resistance $\partial U_{\text{tube}}/\partial I_{\text{tube}} < 0$. This typical $I - V$ characteristic with a large voltage required for plasma breakdown and a negative local resistance implies that sustaining the plasma in the tube is an easy task once it has been created. The negative resistance $\partial U_{\text{tube}}/\partial I_{\text{tube}} < 0$ also requires current limitation, achieved by the magnetic ballast, whose resistance R_b and inductance L_b have been measured to be 30 Ω and 1 H respectively. This results in a ballast inductance Z_b:

$$Z_b = \sqrt{R_b^2 + (2\pi f_{\text{mains}} L_b)^2} \sim 315\ \Omega$$

larger than the tube impedance (of the order of 50 Ω), which typically limits the rms intensity of the current to $240/Z_b \sim 0.8$ A.

2.1.2. Influence of filament temperature on plasma breakdown. The ignition, or breakdown, of a plasma within a tube of length d at pressure p submitted to an electric field $E = U_{\text{tube}}/d$ is a well-known physical phenomenon [5, 6, 21, 22]. It involves (i) exponential growth of electrons accelerated by the electric field from ionizing collisions with the neutral gas, and (ii) electron emission at the cathode. At low cathode temperature, the latter is dominated by secondary electron emission from ion bombardment, usually characterized by a coefficient γ, which specifies the number of secondary electrons per incident particle. The voltage breakdown between two electrodes spaced apart by distance d is then expressed using Paschen's law [22]:

$$U_b = \frac{Bpd}{\ln(Apd) - \ln[\ln(1 + 1/\gamma)]}, \tag{1}$$

where A is the saturation ionization of the gas under consideration and B is related to the ionization energy of the gas. For noble gases, both of these coefficients increase with the atomic mass [23].

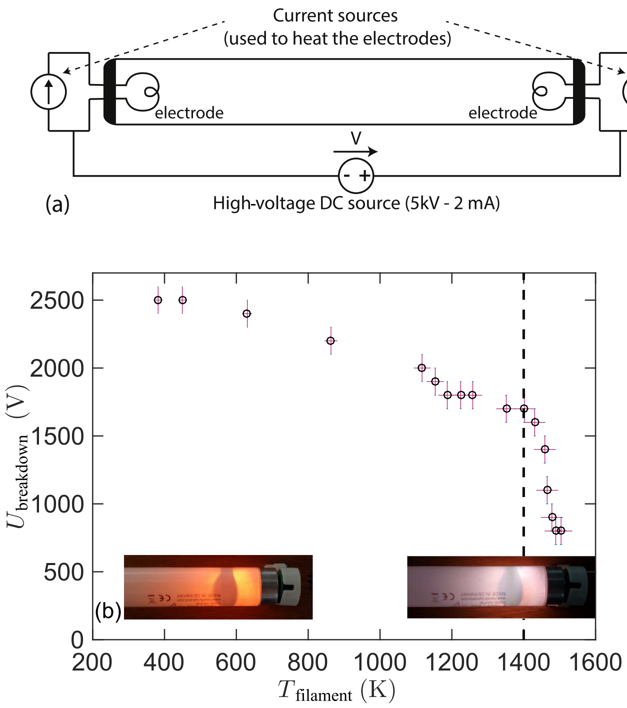

Figure 3. Influence of filament temperature on breakdown voltage: (a) experimental setup, (b) voltage breakdown as a function of T_{filament}. The vertical dashed line indicates the visual modification of the tube. See text for details.

When electrodes are heated up, a second process, thermionic emission, adds to secondary electron emission. The ability of a material to emit electrons from the thermionic effect increases with its temperature T, following Richardson's law as $T^2 \mathrm{e}^{-eW/k_\mathrm{B}T}$ with k_B the Boltzmann constant, e the electron charge and W the work function [24, 25]. In our experimental setup, the increase of the filament temperature T_{filament} is expected to increase the value of the *effective* γ coefficient and to reduce the breakdown voltage. This effect is directly measured using the dedicated setup displayed in figure 3(a). Both electrodes are Joule-heated by the same DC current, driven from two independent DC power supplies. The measurement of the voltage U_{filament} across the filament allows for the computation of the resistance of the filament R_{filament} and its temperature is inferred assuming a local power balance between Joule heating and losses by radiation (an assumption valid at a high enough filament temperature and low enough pressure in the tube) [26, 27]. Assuming that the core filament is pure tungsten, the temperature is computed from the following equation [28, 29]:

$$T_{\text{filament}} = T_0 \left(\frac{R_{\text{filament}}}{R_0} \right)^{1/1.2} \tag{2}$$

where R_0 is the resistance at room temperature T_0. Equation (2) is typically valid above 150 K (see, for instance, the log-log plot on page 1092 of [30]). A high-voltage DC power supply (up to 3 kV) is used to bias the fluorescent tube between the hot electrodes. The DC voltage at which plasma breakdown occurs is reported as a function of T_{filament} in figure 3(b). The filament temperature is thus shown to have a strong impact on the breakdown voltage. An abrupt decrease of breakdown voltage is evidenced above 1400 K. This filament temperature

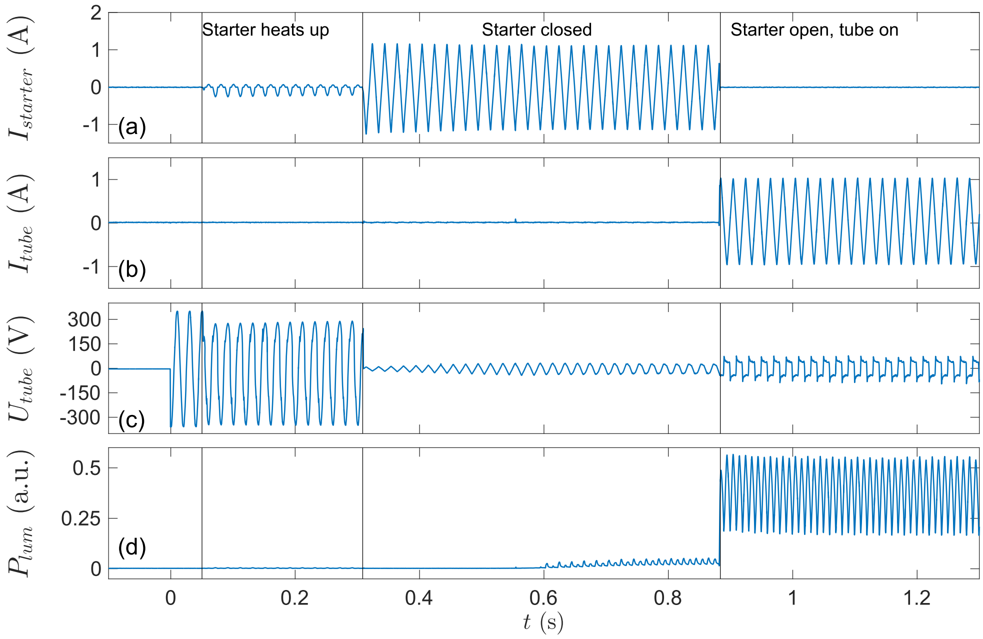

Figure 4. Time series of (a) starter current (or filament current) I_{starter}, (b) current in the tube I_{tube}, (c) voltage across the tube U_{tube} and (d) light intensity P_{lum} showing a typical tube-startup time sequence for a tube initially at ambient temperature. See text for details.

is associated with a visual modification of the light emitted by the tube, even in the absence of a external bias between the filaments. Below 1400 K, the light emitted by the filaments is due to thermal radiation and filaments appear reddish (see figure 3, bottom-left photograph). Above 1400 K, the temperature is high enough to trigger electron emission and the voltage across the filament locally sustains a plasma; UV radiated by the plasma excites the phosphor coating which, in turn, emits white light (see figure 3, bottom-right photograph).

2.2. Time analysis of normal startup

Let us now investigate the temporal dynamics of normal startup as the electric power of the tube is fed by the mains as displayed in figure 4. At time $t = 0$, the mains are switched on: the line voltage (rms voltage of 240 V) is applied to the tube and the starter, but no current flows. At $t \sim 0.05$ s (identified by vertical lines in figure 4), the gas enclosed in the starter capsule becomes ionized: a weak current of the order of 50 mA crosses the starter during the positive voltage half-wave and the bimetallic strip enclosed in the starter heats up. At $t \sim 0.31$ s (identified by vertical lines in figure 4) the deformation of the bimetallic strip is large enough to close the electrical circuit (referred to as a 'closed starter' in the remainder of this paper) and a current of typically 1 A flows in the starter and the filament electrodes. This large current leads to Joule heating of the filaments, while the starter cools down (as no plasma is present in the starter). Finally, at $t \sim 0.88$ s (identified by vertical lines in figure 4) the starter opens, leading to a large over-voltage across the tube, exceeding the breakdown voltage and igniting the plasma in the tube. Note that light emission is modulated at 100 Hz, with maxima for each half-wave of the mains voltage [15].

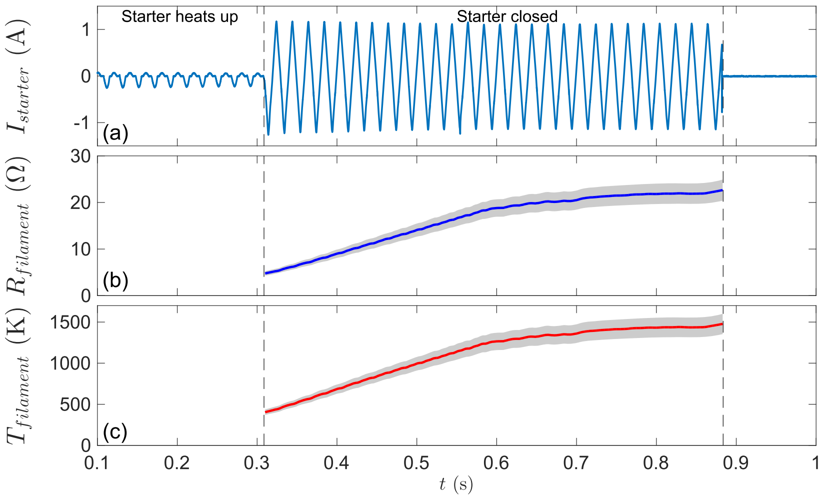

Figure 5. Time evolution of (a) starter current (or filament current), (b) R_{filament}, and (c) T_{filament} during pre-heating phase, when the starter is closed. Error bars displayed as areas shaded grey. See text for details.

The startup process thus strongly relies on the pre-heating of the electrodes when the starter is closed. The temporal evolution of the current flowing in the starter, the filament resistance and the filament temperature during the pre-heating phase is displayed in figure 5. The filament resistance was measured as the ratio of the envelope of the filament voltage over the envelope of the starter current (this is valid as long as no plasma is present in the tube, i.e. when $I_{\text{tube}} = 0$), and reaches a few tens of ohms (error bars are displayed as the area shaded grey). The resistance of both electrodes (typically less than 50 Ω) remains at least five times lower than the ballast impedance ($Z_b \sim 315\ \Omega$); as a consequence, the amplitude of the current flowing in the filament remains roughly constant during pre-heating, while the voltage across the filament increases (not shown). The time evolution of the filament temperature T_{filament}, computed from equation (2), is displayed in figure 5(c). After a few tenths of a second of pre-heating, T_{filament} reaches values around 1500 K, i.e. at the onset of emission due to the thermionic effect, which decreases the breakdown voltage to ignite the plasma, as described in section 2.1.2.

3. Flickering regimes

Flickering regimes observed at the startup of aged fluorescent tubes involve faulty startups, i.e. plasma breakdown is reached transiently, but the plasma within the tube is not steadily sustained. Based on the previous observations, this is likely to be related to inefficient pre-heating of the filaments. In aged fluorescent tubes, thermionic emission might be decreased due to sputtering of the filament's emissive layer, oxidation of the emissive layers, or deposition of other materials on these emissive layers. Note that sputtering or evaporation of the filaments would lead to a gradual decrease of the filament's diameter and to a gradual increase of $R_{\text{filament}}(T_0)$. However, this effect is likely to be counter-balanced by the sputtering of the strongly emissive layers: the thermionic effect from the bulk filament material is likely to be lower than that from the emissive layer. On the other hand, modification of the gas composition could also lead to a change of breakdown voltage. Ageing of the starter could

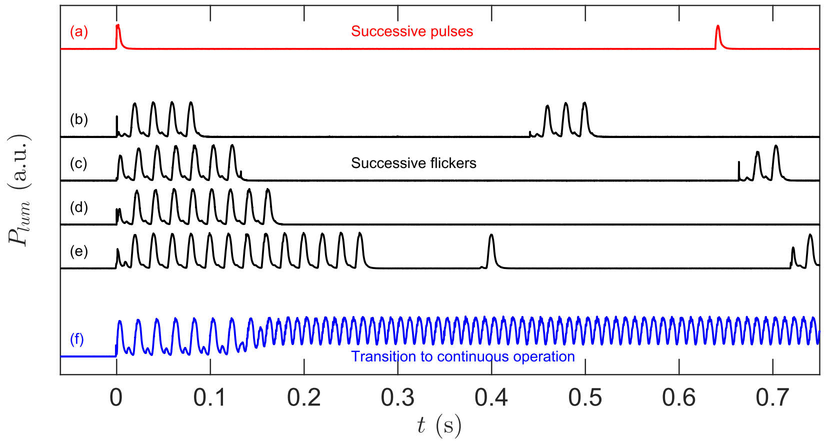

Figure 6. Typical time traces of flashes observed as R decreases from 910–457 Ω (top to bottom). See text for details.

also lead to a decrease of the duration of the closed time, which would then lead to less efficient pre-heating. However, we postulate that the leading process controlling the tube ignition is thermionic emission from the electrodes. In this framework, faulty startups using functional fluorescent tubes can be obtained when decreasing the temperature of the filament (since thermionic emission depends exponentially on the material's temperature according to Richardson's law). In order to experimentally simulate the inefficient pre-heating of the filaments, an additional high-power resistance R was inserted in series with the ballast, as shown in figure 1. This additional resistance reduces the amplitude of the current flowing in the filaments, which lowers the efficiency of the pre-heating. An order-unity decrease of the current flowing in the filaments has a strong effect on the Joule heating of the filaments, which in turn has a strong influence on the thermionic effect. As a consequence, the value of the additional resistance R was chosen to be a few times that of the ballast's impedance $Z_b \sim 315\ \Omega$. Flickering light emission from the tube was observed for R values in the range 500–1000 Ω. For R values greater than 1000 Ω, no light emission was observed. Note that similar results have also been observed when decreasing the voltage amplitude feeding the circuit with $R = 0$ (for instance, using an autotransformer between the mains and the circuit), which also reduces the current flowing in the filaments during the pre-heating phase.

3.1. Description of flickering regimes

Several flickering regimes have been observed depending on the value of the additional resistance R, and typical time series of light emission are reported in figure 6 (for the sake of clarity, time series are vertically shifted). The regime shown in figure 6(a) consists of a random distribution of short pulses, and was observed for R values in the range of 910–550 Ω. In this regime, the plasma is sustained only during a fraction of a single half-period of the mains 50 Hz cycle: a single peak of light emission is observed before fading out. As the value of R decreases, light emission is no longer limited to short pulses, as shown in figures 6(b)–(e). The plasma may be sustained in the tube during several mains cycles, leading to a flickering regime consisting of a train of pulses of light emission. Note that the light is modulated by 50 Hz during one flicker, which is highly uncomfortable for the human eye—it is shown later that the plasma is only sustained during a given polarity of the mains.

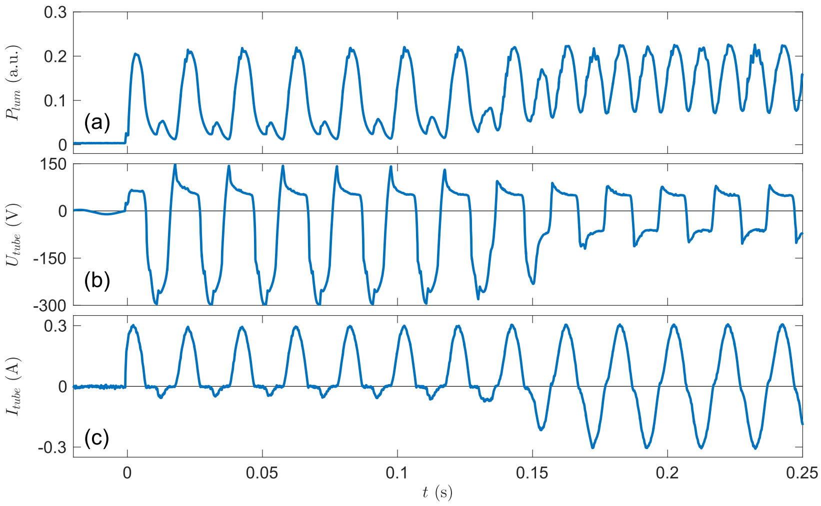

Figure 7. Time evolution of (a) light intensity P_{lum}, (b) voltage across the tube U_{tube}, and (c) the plasma current I_{tube} for the regime reported in figure 6(f), $R = 457\ \Omega$. See text for details.

Successive flickers may be excited as reported in figures 6(b) and (c) or may alternate with short pulses, as reported in figure 6(e). Finally, for R values lower than 500 Ω, the flickering regime slowly drifts and finally leads to normal operation of the tube, as shown in figure 6(f). Note that in this last regime, and for times larger than 0.2 s, the light is modulated at 100 Hz as is the case during normal operation. However, the introduction of the additional resistance $R \sim 1.5Z_b$ reduces the light intensity by a factor around 2.5.

The detailed analysis of the regime reported in figure 6(f) is instructive. Simultaneous time series of light intensity P_{lum}, voltage across the tube U_{tube}, and plasma current I_{tube} are reported in figure 7. For $0 < t < 0.12$ s, significant light emission is only observed when the voltage across the tube is positive: the plasma is only sustained during a given polarity of the 50 Hz cycle, resulting in a 50 Hz modulation of light emission. This is likely to originate from the efficient pre-heating of only one of the two filaments, say electrode 1. During the positive voltage half-wave, plasma breakdown is obtained when electrode 1 acts as the cathode, while breakdown is not reached when electrode 1 acts as the anode, i.e. during the negative voltage half-wave (not that the scale of figure 7(b) is not symmetric). It is important to note that, since thermionic emission exponentially increases with temperature according to Richardson's law, a very weak temperature difference between both electrodes leads to a large difference in current emitted by the thermionic effect. Weak geometric or assembly asymmetries between both electrodes are thus expected to result in a strong difference in thermionic emission at the onset. However, as electrode 2 is further heated by ion bombardment and current injection into the plasma, it acts as an increasingly efficient cathode for $0.12 < t < 0.18$ s. Finally, a symmetric behaviour is recovered for times larger than 0.2 s, resulting in a 100 Hz modulation of light emission, as reported in section 2.2. The asymmetric regime may thus only be obtained transiently and in a narrow range of parameters.

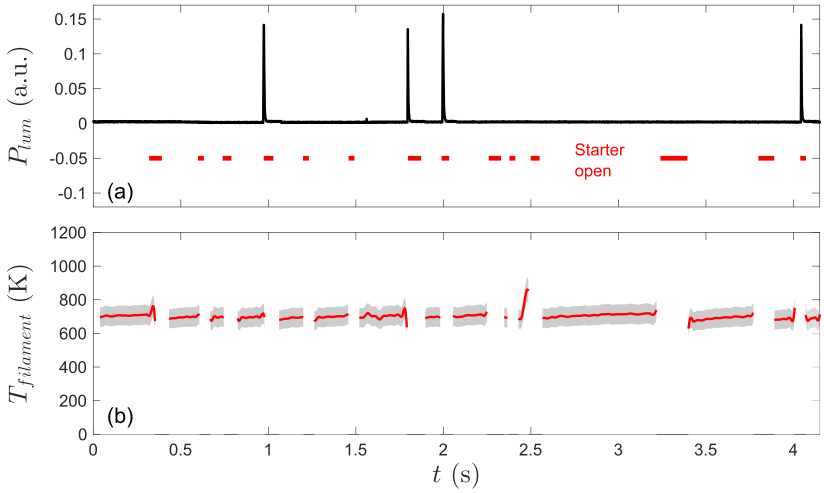

Figure 8. Time evolution of (a) light intensity P_{lum} and (b) filament temperature T_{filament}. Open starter phases identified by red lines on panel (a).

3.2. Time statistics of flickers

3.2.1. How flicker onset is related to the opening of the starter. The common experience of aged and flickering fluorescent tubes links flickering light emission to sound emission from the starter. As long as no plasma is sustained in the fluorescent tube, the voltage across the starter is high enough to reach breakdown of the starter gas; as a consequence, the starter continuously alternates between closed and open phases. Plasma breakdown in the tube necessarily occurs at the opening of the starter, as shown in the previous section. However, as shown in figure 8(a), light-emission pulses do not systematically coincide with the opening of the starter (shown as red lines in the top panel). In our experimental setup, the inefficient pre-heating of the filaments requires the opening of the starter within a short period of the 50 Hz mains to ensure plasma breakdown in the fluorescent tube. Indeed, plasma breakdown requires a high enough over-voltage across the ballast (which depends on the value of the current at the opening time), and during the positive polarity of the 50 Hz mains voltage (as described in the previous subsection). For these reasons, plasma breakdown is not observed for all opening events of the starter. The filament temperature T_{filament} is reported in figure 8(b), and shows that a stationary regime for the filament temperature is reached, allowing for the statistical analysis of flickering regimes. The regime reported in figure 8 consists of single pulses, but it is important to note that, for longer flickers, the opening of the starter is not systematically associated with light emission. The time distribution of light flickers is investigated in detail in the next two subsections; for the sake of simplicity, the temporal dynamics of the opening/closing sequences of the starter are not investigated explicitly.

3.2.2. Statistics of single pulses. First, let us investigate the statistics of successive single pulses (i.e. the regime reported in figure 6(a)) for R values in the range (550–910 Ω). Pulses typically last less than 5 ms and do not strongly change from one pulse to the other. We thus focus our attention on the distribution of the waiting times between two successive pulses. One hour-long acquisitions were acquired for several values of the additional resistance R. The photodiode signal is used to trigger a fast oscilloscope (with a 5 ms time base) and the

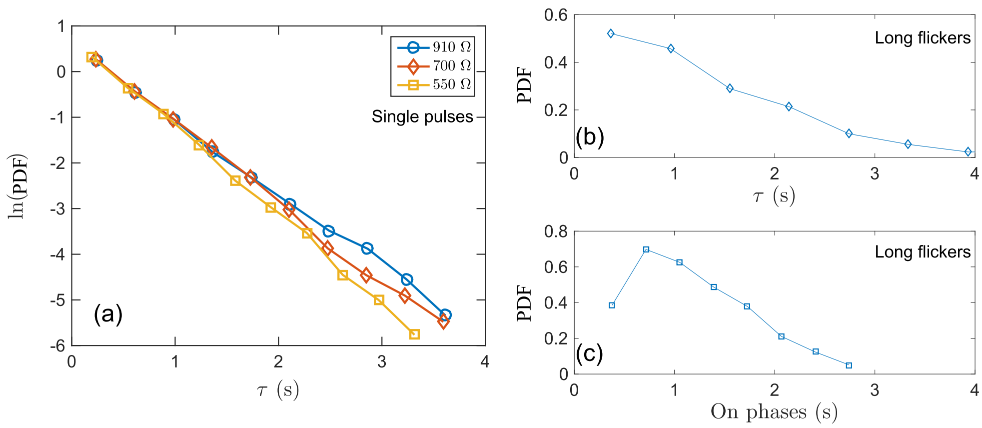

Figure 9. (a) Probability distribution function of waiting times τ for the successive pulses regime reported in figure 6(a) for three values of R. Probability distribution functions of (b) waiting times τ and (c) on-phases for the long flickers reported in figure 6(e).

digital TTL trigger-out signal of the oscilloscope is acquired at a rate of 250 Hz. The probability distribution functions (PDF) of the waiting times are displayed in figure 9(a) for three values of R and are consistent with exponential distributions. The pulses thus appear to be randomly distributed, without any correlation between occurrences. The characteristic mean waiting time $\langle\tau\rangle$ between two pulse times weakly evolves with R: $\langle\tau\rangle$ decreases from 0.62 s to 0.57 s and finally 0.51 s as R decreases from 910 to 700 and finally 550 Ω respectively. It is important to note that this decreasing trend is observed since the tails of the PDFs are fairly well resolved. As the value of R decreases, the current in the pre-heating phase increases, and the plasma is more likely to ignite: the increase of the filament's temperature make them more emissive and the increase of the current increases the over-voltage $L_b \mathrm{d}I/\mathrm{d}t$ across the magnetic ballast. As a consequence, the mean waiting time slowly decreases with decreasing values of R.

3.2.3. Statistics of longer flickers. Let us now investigate the statistics of the longer flickers obtained when $R < 550$ Ω, i.e. the regimes reported in figures 6(b)–(e) where both short pulses and longer flickers are present. For a typical configuration with $R = 497$ Ω nearly 700 light-emitting events have been measured over 1800 s, out of which 61% are long flickers (lasting at least two mains cycles). Note that these regimes with long flickers are extremely unstable: a slow time evolution of the filament temperature could lead either to recovery of a symmetric behaviour leading to continuous light emission or to recovery of regimes consisting of a succession of short pulses. Our study focuses on two distinct PDF: namely those of the duration of on-phases (i.e. the duration of the flicker light emission), and the PDF of the duration of waiting times (or equivalently, off-phases). The distribution of waiting times, shown in figure 9(b), decreases monotonically, while the distribution of on-phases, shown in figure 9(c), clearly peaks with the most probable value around 0.7 s and a long tail towards large values. Finally, note that the distributions shown here should be regarded as illustrative due to the unstable behaviour in this range of parameters (the fluorescent tube was finally continuously emitting light at the end of the time series under investigation). As a consequence, the deviation of the waiting-time distribution from an exponential distribution might be due to the non-stationarity of the regime—since the physical origin of the flicker onset is the same as for the pulses, one would expect the distributions to be similar. Addressing this issue would require careful control of the stability of the flickering regime.

4. Conclusion

The physical processes controlling the startup of fluorescent tubes used with a magnetic ballast and a starter were investigated experimentally, using an inexpensive and easy-to-reproduce experimental setup. The ability of the electrodes at each end of the fluorescent tube to emit electrons is shown to be the leading parameter controlling the voltage required across the fluorescent to achieve plasma breakdown. In particular, for a given tube assembly, electron emission from thermionic emission is controlled by the temperature of the electrodes. A detailed time sequence of the startup of fluorescent tubes is reported, including detailed experimental measurements of the electrode temperature. Finally, the inability of aged fluorescent tubes to undergo quick ignition is experimentally addressed. In this regime, light-emission flickers and random-noise emission are experienced at startup. An experimental method to simulate flickering regimes using standard tubes is introduced. This relies on reducing the current heating the electrodes when the starter is closed since the flickering regime originates from inefficient pre-heating of the electrodes, which only transiently sustains the plasma in the fluorescent tube. In particular, in our experimental setup, flickers are observed when only one of the electrodes reaches a temperature high enough to strongly emit electrons when negatively biased. Using this method, statistically stationary flickering regimes are observed, allowing for the statistical analysis of the time distribution of flickers. The onset of flickers appear to be random in time, with no correlation, resulting in an exponential probability distribution function.

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