The plasma ball in physics teaching: A classroom approach to plasma ionization

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Received: July 14, 2025 DOI: 10.14295/bjs.v4i10.768

Accepted: September 24, 2025 URL: https://doi.org/10.14295/bjs.v4i10.768

Abstract

Plasma is recognized by Physics as the fourth state of matter. However, the study of plasmas in schools and universities often faces challenges, mainly due to the high cost of science and physics laboratories, which can be inaccessible to many groups of students. As a viable and affordable alternative, devices such as the plasma ball have been used in teaching this physical state of matter, even allowing the quantification of electric fields and the observation of electromagnetic waves. This study aimed to use a low-cost plasma ball in teaching a university-level Physics class, enabling hands-on experiments related to the determination of electric and magnetic fields. For this purpose, a low-cost digital sensor for electromagnetism and electric fields, a neon lamp, and a metallic coin were used. Students learned how to calculate the power of the plasma ball and explore the concepts of electric fields and electromagnetism, when present. The introduction of simple and engaging teaching tools significantly contributed to the students' involvement. They showed increased interest and ease in understanding the concepts related to the Physics of Electromagnetic Interactions (Electromagnetism), highlighting the pedagogical potential of accessible instruments in the teaching-learning process. Therefore, Physics classes must include basic, low-cost equipment or materials that can be easily constructed from readily available resources to enhance the teaching of this exact science.

Keywords: electric field, electromagnetic field, teaching-learning, fourth state of matter, electric field sensor.

A bola de plasma no ensino de física: uma abordagem em sala de aula para a ionização de plasma

Resumo

O plasma é reconhecido pela Física como o quarto estado da matéria. No entanto, o estudo de plasmas em escolas e universidades frequentemente enfrenta desafios, principalmente devido ao alto custo dos laboratórios de ciências e física, que podem ser inacessíveis a muitos grupos de alunos. Como alternativa viável e acessível, dispositivos como a bola de plasma têm sido utilizados no ensino desse estado físico da matéria, permitindo inclusive a quantificação de campos elétricos e a observação de ondas eletromagnéticas. Este estudo teve como objetivo utilizar uma bola de plasma de baixo custo no ensino de uma aula de Física de nível universitário, possibilitando experimentos práticos relacionados à determinação de campos elétricos e magnéticos. Para tanto, foi utilizado um sensor digital de baixo custo para eletromagnetismo e campos elétricos, uma lâmpada neon e uma moeda metálica. Os alunos aprenderam a calcular a potência da bola de plasma e a explorar os conceitos de campos elétricos e eletromagnetismo, quando presentes. A introdução de ferramentas de ensino simples e envolventes contribuiu significativamente para o envolvimento dos alunos. Eles demonstraram crescente interesse e facilidade na compreensão dos conceitos relacionados à Física das Interações Eletromagnéticas (Eletromagnetismo), destacando o potencial pedagógico de instrumentos acessíveis no processo de ensino-aprendizagem. Portanto, as aulas de Física devem incluir equipamentos ou materiais básicos, de baixo custo e de fácil construção a partir de recursos prontamente disponíveis, para aprimorar o ensino desta ciência exata.

Palavras-chave: campo elétrico, campo eletromagnético, ensino-aprendizagem, quarto estado da matéria, sensor de campo elétrico.

1. Introduction

Experimental practices represent an essential methodological tool in the teaching and learning process of Physics, especially due to their interactive and investigative nature. Several studies highlight the benefits of such approaches, both in enhancing student learning and in fostering interest in this subject within the field of the exact sciences (Hiha; Oliveira, 2012; Pereira; Robaina, 2020; Souza et al., 2021). Furthermore, hands-on activities are widely accepted by both teachers and students, as they allow for the direct observation of physical phenomena and the critical analysis of the theories that explain them, promoting more meaningful and contextualized learning.

However, the teaching of Physics in school and university contexts still faces significant challenges, particularly regarding the approach to abstract or underexplored concepts within the traditional curriculum. A notable example is the study of physical states of matter beyond the conventional solid, liquid, and gas states, such as plasma, which is recognized as the fourth state of matter (Chen, 2015). Although it constitutes more than 99% of the visible matter in the universe, plasma is rarely addressed in the classroom, mainly due to the difficulty of direct experimentation and the lack of accessible didactic resources that facilitate its understanding (Freidberg, 2008).

In this context, devices such as the plasma ball emerge as effective pedagogical alternatives to visually and interactively illustrate phenomena associated with gas ionization, electric fields, and conductivity in ionized media. This tool is not only visually appealing but also accessible and feasible for Physics education. The plasma ball allows the direct observation of luminous filaments produced by electrical discharges in rarefied gases (Arthury et al., 2022). According to Yunusov & Yunusova (2020) and Erthal et al. (2014), plasma consists of an electrically conductive and interactive combination of a significant number of charged and neutral particles, including positive ions, free electrons, and electric and magnetic fields.

This experimental resource sparks students' curiosity, promotes active learning, and supports a more concrete understanding of key concepts such as ionization, electrical discharges, electromagnetic fields, and electric conduction in plasmas (Erthal et al., 2014). Moreover, its integration into the teaching-learning process aligns with the National Common Curricular Base (BNCC) guidelines, which emphasize experimentation, content contextualization, and student protagonism in the construction of knowledge (Zhao et al., 2023).

Therefore, this article aims to review and discuss the use of the plasma ball as a didactic tool in Physics education at the higher education level, focusing on classroom approaches to plasma and its ionization, and analyzing its pedagogical potential, limitations, and applicability in the university context.

2. Theoretical Framework

2.1 Plasma as the fourth state of matter

Plasma is recognized as the fourth state of matter, distinct from the solid, liquid, and gaseous states. It is an ionized gas composed of charged particles, such as positive ions and free electrons, which exhibit collective behavior under the influence of electric and magnetic fields (Chen, 2015). Plasma formation occurs when a gas is subjected to high temperatures or strong electric fields, causing its atoms to lose electrons and become ionized (Freidberg, 2008).

Although plasma accounts for more than 99% of the visible matter in the universe—being present in stars, lightning, auroras, and the interstellar medium—its study remains limited in formal Physics education, particularly at the secondary and undergraduate levels (Erthal et al., 2014). This limitation is mainly due to the challenges of producing plasma in a controlled manner within educational environments, as well as the lack of accessible didactic materials.

As described by Erthal et al. (2014), plasma consists of an electrically conductive and interactive mixture of a large number of charged and neutral particles, such as ions and electrons, along with electric and magnetic fields. These characteristics give plasma unique properties, including high electrical conductivity, responsiveness to electromagnetic fields, and light emission, distinguishing it from the other states of matter.

2.2 The plasma ball as a didactic resource

The plasma ball is a device invented by Nikola Tesla in the 19th century and later popularized as a scientific demonstration tool. It consists of a glass sphere filled with rarefied gas (typically neon, argon, or xenon) and equipped with a central electrode powered by a high-voltage, high-frequency source. The electric discharge inside the sphere ionizes the gas, generating luminous filaments that extend from the center toward the glass surface (Azpeitia; Pons, 2019; Arthury et al., 2022).

This device enables the direct observation of gas ionization, electrical discharges, and interactions with electric and magnetic fields. As such, it serves as a highly effective resource for teaching abstract Physics concepts, such as the behavior of charged particles, electrical conduction in ionized media, and plasma properties (Erthal et al., 2014; Arthury et al., 2022).

In addition to its visual appeal, the plasma ball is safe and relatively affordable, making it suitable for use as a pedagogical tool in classroom settings. According to Zhao et al. (2023), the integration of interactive experimental resources in science education aligns with the guidelines of the Brazilian National Common Curricular Base (BNCC), which emphasizes student agency, experimentation, and content contextualization.

The use of the plasma ball allows students to observe phenomena that are typically confined to advanced laboratory environments, thereby promoting meaningful learning and stimulating scientific curiosity.

3. Materials and Methods

2.1 The experiments

The plasma ball in operating conditions and its corresponding device are shown in Figure 1. Structurally, the equipment consists of a sealed outer glass container, inside of which there is an inert gas at low pressure. At the center of this container is a hollow glass sphere, internally coated with a conductive material. This conductive coating is connected via a wire to a USB power supply with a DC 5V and 1.0A output, located at the base of the plasma ball structure. During the tests, the inner glass sphere was supplied with a voltage of 5V and a current of 250 mA. The diameter of the outer glass container used in the experiments was 10 cm, with a total power consumption of 1.25 W, as calculated in Equation 1:

$$\text{Power} = 5\,V \times 0.250\,A = 1.25\,W \quad \text{(Eq. 1)}$$

When powered on, the internal electronic circuit converts the input voltage into a high-frequency, high-voltage signal, which is responsible for ionizing the gas and generating the luminous filaments characteristic of plasma.

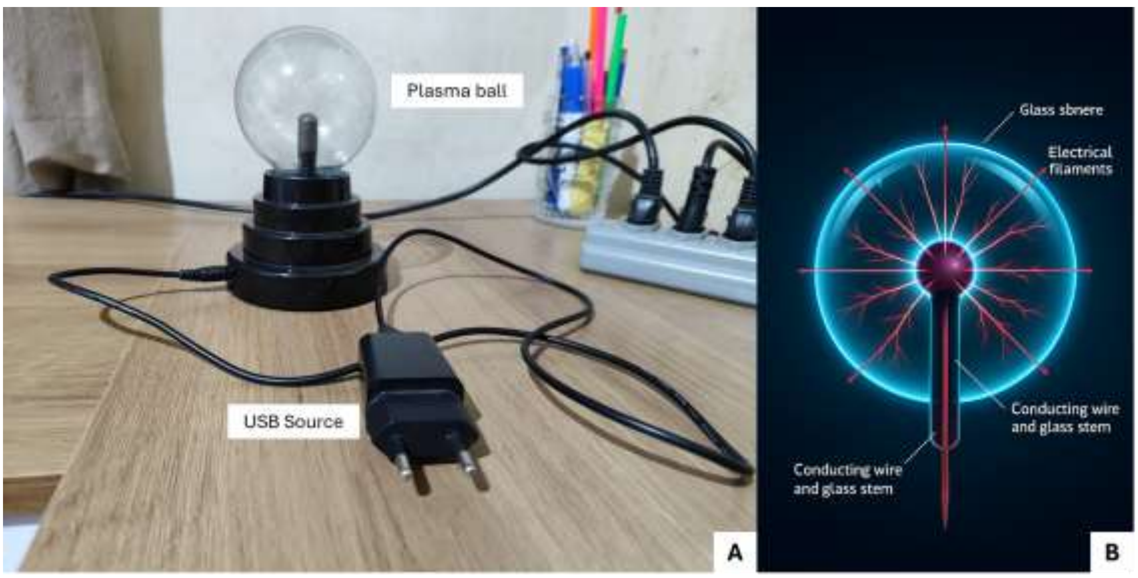

Figure 1. Low-power plasma ball (**A**) and (**B**) operational schematic. Source: Author, 2025.

3.2 Electromagnetic apparatus

A digital electromagnetic and electric sensor (ST1393, China) EMF tester – Smart Sensor was used, with a measuring range of 0.1~1999 mG, 0.01~199.9 µT, and 0.0~7500 V/m. Transparent neon lamps 220V NE-2, with an ignition voltage of approximately ~90 V (AC), operating voltage around ~60 V, operating current ranging from 0.3 to 2 mA, maximum supported voltage of 220 V (AC), filled with neon gas at low pressure, and non-polarized. Coin made of cupronickel alloy (75% Cu and 25% Ni).

4. Results

4.1 Plasma ball mechanisms

The students were able to observe the formation of plasma inside the globe containing a high-voltage electrode and an inert gas. This phenomenon was also described by Erthal et al. (2014), where the researchers designed an alternative plasma ball for didactic-scientific use.

In the study, the students were prompted with the following questions:

1. What is generated by the plasma ball?
2. The plasma ball operates with high voltage and high frequency, generating what?

In simple terms, plasma is produced by increasing the temperature of a substance until it reaches a high level of ionization. Under thermodynamic equilibrium conditions, the degree of ionization and the electron temperature are related, and this relationship is described by the Saha equation, as shown below (Bittencourt, 2004; Erthal et al., 2014).

$$\frac{n_i}{n_n} = 2{,}405 \times 10^{21}\, T^{\frac{3}{2}}\, \frac{1}{n_i} \exp\left(\frac{-U}{k\,T}\right)$$

The students, equipped with the provided data, were able to analyze different data sources from the plasma and electric field:

Input voltage: 5 V

Input current: 250 mA = 0.25 A

Electric power is obtained according to Equation 1, previously described.

$$\text{Power} = 5\ V \times 0.250\ A = 1.25\ W \quad \text{(Eq. 1)}$$

This power is compatible with small commercial plasma balls like the one used in our experimental Physics teaching setup. They use oscillator circuits to generate high alternating voltage with low current from this modest power supply.

4.2 Assumptions for the model

The students were able to evaluate the assumption behind the model of the didactic plasma ball, even though it operates with a low input power (1.25 W). Internally, however, there is a transformer that increases the voltage to several thousand volts, creating a significant electric field near the glass surface, which was verified.

Thus, the students assumed a reasonable value for the electric field measured at 1 cm from the surface, based on experimental data and the literature discussed in class, where:

Estimated electric field at 1 cm: 5,000 V/m

The formula used to simulate the decay

$$E(r) = \frac{k}{r^2},$$

k = 5.000 x (0.01)2 = 0.5

Figure 2 presents the estimated electric field graph for a common plasma ball (5 V, 250 mA). Near the surface (1 cm): approximately 5,000 V/m. The field rapidly decreases with distance, becoming insignificant beyond 50 cm. This behavior is typical of emitters with high voltage and low current, such as these decorative balls. Yunusov & The relative radius $R = 1$ was defined as a distance of 10 cm from the outer surface of the ionization lamp — the point at which the neon light first turned on. From there, measurements were taken at 1 cm intervals, gradually decreasing the distance while monitoring the current through the lamp and the breakdown voltage of the discharge. Knowing the power dissipated in the neon lamp, it was then possible to calculate the electric field intensity, which was also theoretically addressed in the experiment presented here.

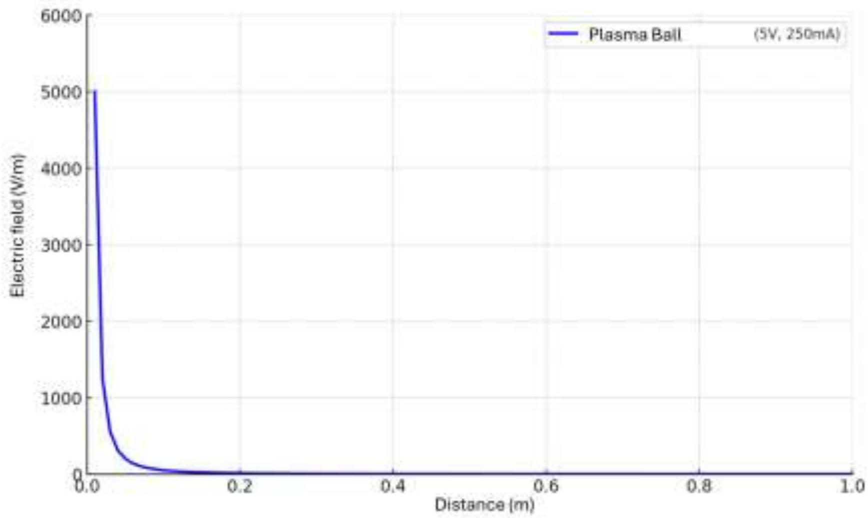

Figure 2. Electric field decay of a low-power plasma ball. Source: Authors, 2025.

In Figure 3, the different stages of the experiment with the plasma ball are presented: (Fig. A) shows the plasma ball turned off, with the detector indicating no electromagnetic emission and electric field intensity of 0 V/m. (B) With the plasma ball activated, the formation of plasma filaments and the presence of an oscillating electric field are observed. The detector, positioned at various distances, records variations in the electric field intensity (V/m). However, no significant electromagnetic radiation (RF) emissions were detected at this stage. Figure 3 (C) illustrates the plasma ball in full operation, with multiple plasma filaments radiating outward. In Figure 3 (D), when a metallic coin is brought near the surface of the glass globe, the plasma filaments are seen to concentrate around the object. Since the coin is made of a conductive material, electric charges are induced on its surface, especially when held by a person. In this case, the human body acts as a grounded conductor, enhancing the electric field effect.

This approximation may result in small visible discharges between the glass and the coin, similar to those seen when touching the globe with a finger. This phenomenon occurs due to the ionization of the air between the glass and the metal, caused by the high voltage applied internally. Students observed a significant increase in the brightness and intensity of the plasma filaments, which prompted them to reflect on the electrostatic behavior of the system:

“The plasma filaments tend to concentrate toward the coin because it represents a path of lower electrical resistance, similar to when a finger touches the globe.”

Figure 3 (E) demonstrates the ability of the electric field generated by the plasma ball to light up small and medium-sized lamps, even though the device is a low-power educational model. This phenomenon was discussed as an example of gas ionization and wireless electromagnetic induction. When brought close to the sphere, fluorescent and neon lamps were observed to flash or faintly illuminate, even without being connected to a socket. This occurs because the gas inside these lamps is excited by the oscillating electric field, becoming ionized and emitting visible light.

This effect was considered highly effective from a didactic standpoint, especially for demonstrating the concepts of gas excitation, conduction in ionized media, and energy transmission through varying fields. In Figure 3 (F), when a finger is placed near the surface of the plasma ball, the filaments concentrate directly at the contact point, becoming brighter and more intense. This happens because the human body, being conductive, offers a preferential path for the electric field lines. The plasma current concentrates in that region, enhancing the visual effect. Although no electric shock is felt, the user may experience a slight tingling or warming sensation at the contact point. Students understood that this is due to the thermal energy released by the concentrated plasma current, and that the glass acts as an electrical insulator, preventing current from passing to the body. It was discussed in class that, although the internal voltage of the plasma ball is high, the current is extremely low, making the touch safe. This experience also allowed for discussion of the local modification of the electric field, as the touch of a finger alters the field distribution around the sphere, which could be detected by sensitive nearby instruments.

Additionally, students understood that the human body, in addition to being conductive, modifies the local electric field, altering filament behavior and demonstrating the interaction between electric fields, conductive materials, and insulators in an accessible and visually impactful way. The plasma ball, currently used as a didactic resource in Physics education and as an ornamental object in homes and science fiction films, is an easily accessible device that captures students' attention and makes the teaching-learning process more engaging.

Figure 3. Simple experiments with a plasma ball: analysis of electric and electromagnetic fields using a detector, a metallic coin, a neon lamp, and human skin contact. Source: Author, 2025.

4. Discussion

The phenomena observed with the plasma ball can be interpreted in the framework of Statistical Physics. The Saha equation describes the partial ionization of gases under thermodynamic equilibrium (Dewan, 1961), relating the concentration of ionized atoms (n_i) and neutral atoms (n_n) to the total particle concentration in the system. The exponential term depends on the ionization energy (U), temperature (T), and Boltzmann constant (k), which are fundamental parameters to explain plasma formation.

During the experiment, students observed variations in the electric field near the glass surface, as well as visible discharge filaments and an oscillating magnetic field. The use of the detector confirmed that the electric field intensity increases close to the sphere, reaching values in the range of hundreds to thousands of V/m, oscillating according to the high-frequency alternating current applied to the central electrode (15–30 kHz). This finding generated productive discussions on the dynamic nature of electric fields and their dependence on distance from the source.

Additionally, electromagnetic interference was noted in sensitive instruments such as AM radios and RF detectors. Although such noise is common in environments with low electromagnetic shielding, in the present experiment, the plasma ball's power did not cause significant oscillations in the detector, highlighting the importance of considering the experimental environment conditions.

Similar results were reported by Yunusov & Yunusova (2020), who used a plasma globe in didactic experiments to quantify the electric field. The authors emphasized that when the globe is touched, the discharge channels concentrate toward the observer's finger, an effect explained by electrostatic induction. This phenomenon was also recognized by the students, strengthening the practical understanding of theoretical concepts.

From a pedagogical perspective, the experiment reinforced the importance of social interaction in learning, as proposed by Vygotsky's sociocultural theory (Panhwar et al., 2016; Rahmatirad, 2020). Knowledge exchange among peers, mediated by the teacher, enabled students with greater difficulties to engage in the activity, transforming initial apprehension into curiosity and cooperation.

Therefore, the use of the plasma ball proved to be effective not only for demonstrating physical phenomena related to ionization and electromagnetic fields but also as a teaching tool capable of promoting active and collaborative learning.

5. Conclusions

In this experiment, conducted with an undergraduate Physics class, students were able to observe conduction and induction phenomena using a coin and a neon lamp. It was found that the noble gas inside the lamp undergoes excitation and ionization due to the action of the oscillating electric field, as detected by a digital sensor for electromagnetism and electric fields. Furthermore, the plasma ball proved to be a versatile tool, enabling the execution of various experiments in both Physics and Chemistry courses.

The use of simple, low-cost instruments such as this plasma generator can have a positive impact on scientific innovation processes in Brazil, particularly given the multidisciplinary nature of the subject. Ultimately, understanding the basic principles of plasmas contributes not only to students' scientific education but also to the development of citizenship and a more integrated, global perspective of knowledge.

7. Authors' Contributions

Antonio Carlos Pereira de Menezes Filho: Conceptualization, Methodology, and Practical Apparatus Design, Formal Analysis and Data Interpretation, Writing – Original Draft (Project, Analysis, Discussion), Writing – Review & Editing (Corrections), and Supervision and Final Approval for Publication.

8. Conflicts of Interest

No conflicts of interest.

9. Ethics Approval

Not applicable.

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Funding

Not applicable. Whenever public or private funding is involved, its source must be presented.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.