Contributed Review: Review of thermal methods for space charge measurement

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Contributed Review: Review of thermal methods for space charge measurement

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The space charge accumulation phenomenon has garnered great interest over the last two decades because of the increased use of direct current in high voltage electrical systems. In this context, a significant relevance has been achieved by the thermal methods, used for solid dielectrics. This paper presents a review of this non-destructive measurement system used for the measurement of space charge. The thermal pulse method, the thermal step method, and the laser intensity modulation method are described. For each configuration, the principle of operation, the thicknesses analyzed, and the spatial resolution are described, reporting also the main related applications. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4968029]

I. INTRODUCTION

Dielectric materials used as insulation in electrical systems are affected by an electrical degradation, due to several factors.[1]

Under AC stress, the partial discharges are the main cause of aging, especially when an air void is present inside the insulting material.[2,3] Under DC stress, the most relevant aging factor is due at the space charge accumulation phenomenon.[4] For instance, High Voltage Direct Current (HVDC) cables made of Cross-Linked PolyEthyline (XLPE) are affected by degradation due to the distortion of the electric field with respect to the Laplacian field (ideal case), causing strong local stresses.[1–4]

Due to the relevance of the space charge because of its negative effects, over the last decade the methods for space charge measurement in the field of insulation system diagnostics have acquired great interest and have been widely studied and improved. Thus, in order to overcome the challenges related to this phenomenon, many research groups have been interested in the physics of this phenomenon both in the past years[5–9] and in recent years.[10–12]

In particular, many nondestructive methods for the characterization of dielectrics materials from the viewpoint of space charge accumulation have been developed. These measurement systems can be classified into three main families: acoustic and thermal methods for measurements on solid dielectrics and optical methods for measurements also in liquid dielectrics.[13,14]

This review provides an overview on the thermal methods, describing their working principle, their different configurations, their applications, the thicknesses analyzed, and the spatial resolution, with data updated to 2016. In addition, more details on the historical evolution of this method are provided, highlighting the technological challenges and taking into consideration the advantages of the different configurations of the measuring cell.

All the reviewed methods with the related characteristics are summarized in Figure 1.

II. THE THERMAL METHODS

This type of non-destructive measurement systems can be classified into three main categories:

- Thermal Pulse Method (TPM)
- Thermal Step Method (TSM)
- Laser Intensity Modulation Method (LIMM)

The main difference between these categories consists in the modality of application of the thermal gradient to the sample. More in detail, this gradient can either be a thermal pulse from a flash of light or a thermal step by using a thermal diffuser or a sinusoidal modulated heating by means of a laser beam.

In the TPM case, the output signal is a voltage response related to the charge and polarization distribution and to the temperature change. In the TSM and LIMM methods, instead, the output signal is a current response. In the first method, the current is connected to the electric field and to the thermal step. In the second method, this current is related to the temperature, material characteristics, and the space charge.[14]

These methods have in common a satisfactory value of spatial resolution, which can be further improved through greater accuracy in measurements over the surface and internal temperature of the sample.[15,16] There are many works that revised the methods described above, such as Refs. 13, 14, and 17–21, but the comparison of some techniques is reported in Refs. 22–25. In a recent review article Singh[21] also reports the main causes of error encountered in these methods.

A. The thermal pulse method

The TPM has been introduced in 1976 by Collins,[26,27] and its principle of operation is represented in Figure 2. This method is based on a thermal pulse generated by a flash of light (8 μs of duration), which acts on one of the double-metalized surfaces of the sample. A thermal transient is then generated over the sample, and an electrical signal carrying information on the space charge distribution inside the sample itself[13,14] is taken as output.

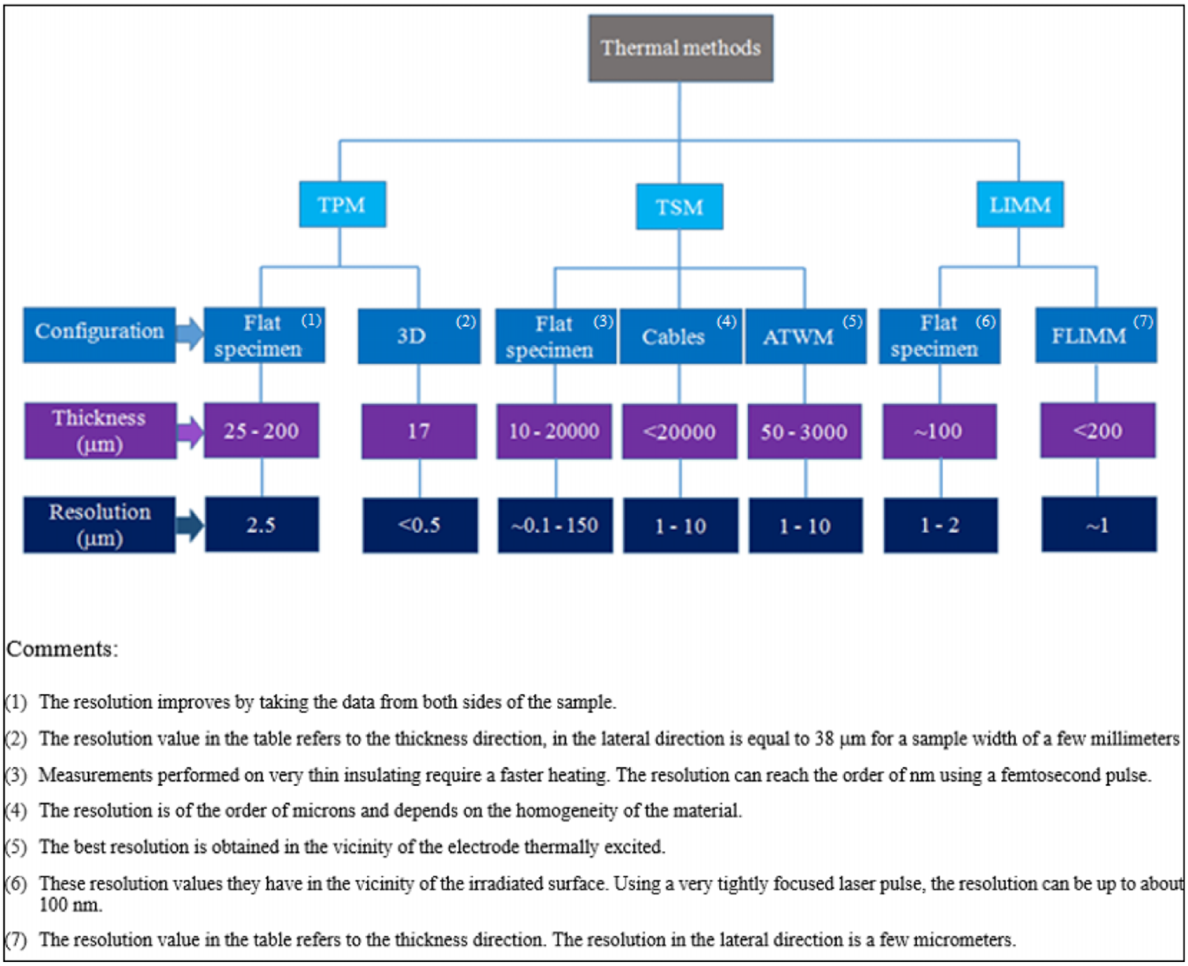

FIG. 1. Overview of the resolution value and thicknesses used in the different thermal techniques.

The system response $\Delta V(t)$ depends on the distribution of the space charge $\rho(x)$ and the polarization $P(x)$. In addition, as shown from Eq. (1), $\Delta V(t)$ depends also on the characteristic parameters of the insulating material, such as the coefficient of thermal expansion α_x, the dielectric constant ε_r, its temperature coefficient α_ε and, finally, the coefficient of permanent polarization α_p,

$$\Delta V(t) = \frac{1}{\varepsilon_r \varepsilon_0} \int_0^d \left\{ \left[A\rho(x) - B\frac{dP(x)}{dx} \right] \int\limits_0^x \Delta T(x')dx' \right\} dx, \tag{1}$$

where $A = \alpha_x - \alpha_\varepsilon$, $B = \alpha_p - \alpha_x - \alpha_\varepsilon$ and d is the sample thickness.

However, the TPM has not been widely used because of the difficult interpretation of the signal for the determination of the real distribution of space charge.

In order to solve this issue, several deconvolution techniques have been developed and presented in literature, from Collins[27] through Mopsik[28] and Zheng.[29]

Over the years some improvements in terms of resolution were proposed by Von Seggern and DeReggi.[30–33] In Ref. 34 the space charge distribution was measured in a silicon dioxide of 1 μm thickness by using a short laser pulse (70 ps). In Ref. 35 a metal-oxide-semiconductor (MOS) structure with thickness of several hundreds of nanometers was tested. The TPM has been recently adapted by Mellinger and Aryal for both 2D[36] and 3D measurements.[36,37]

B. The thermal step method

The thermal step method has been conceived in 1988 by Toureille,[38] and its principle of operation is based on the application of a thermal step to the ends of the related sample

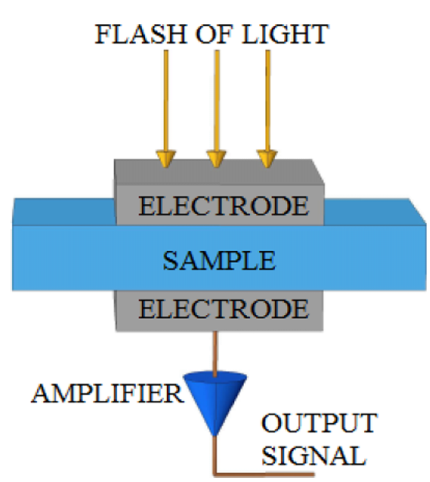

FIG. 2. Working principle of the TPM method.

in order to measure the current response due to the thermal expansion of the sample itself.

More in detail, a thermal diffuser provides a heat step, which creates a thermal wave. This wave will diffuse through the thickness of the dielectric, which determines either an expansion or a contraction of the material, a variation of the insulation permittivity and causing a temporary and reversible displacement of the space charge located within the sample. This displacement will be, then, reflected on the electrodes, determining a variation of the induced charge and, consequently, a current between the electrodes. The value of this current $I(t)$ read by a pico-ammeter (pA) is related to the distribution of both the electric field and the space charge.[39]

This setup is called TSM in short-circuit condition, and the scheme is shown in Figure 3,[14,17,40] while the expression of $I(t)$ is reported in the following equation:

$$I(t) = -\alpha C \int_0^d E(x) \frac{\partial \Delta T(x,t)}{\partial t} dx, \tag{2}$$

where $\alpha = \alpha_x - \alpha_\varepsilon$ (already described in Section II A), C is the capacitance of the sample before the application of the thermal step, d is the thickness of the sample, $E(x)$ is the electric field at the abscissa x, and ΔT the temperature step.

Once $E(x)$ and the dielectric constant of the material ε are known, from Poisson's equation

$$\rho = \varepsilon \frac{\partial E(x)}{\partial x}, \tag{3}$$

the distribution of the space charge can be determined.[41] For this purpose, the adoption of the deconvolution technique is needed, e.g., the Fourier series. This process is accurately explained in Ref. 41 as well as two other techniques, named "process of successive derivatives" and "technique of the inverse matrix." The first method allows the reduction of the deconvolution calculation time, whereas the other one reduces not only the calculation time but also the related error.

Initially, the TSM has been applied for 2-20 mm insulation thicknesses with 150 μm of resolution.[13] However, by means of a faster heating, thin insulations in the range of 10-100 μm with a resolution in the order of tenths of a micrometer can be investigated.[6]

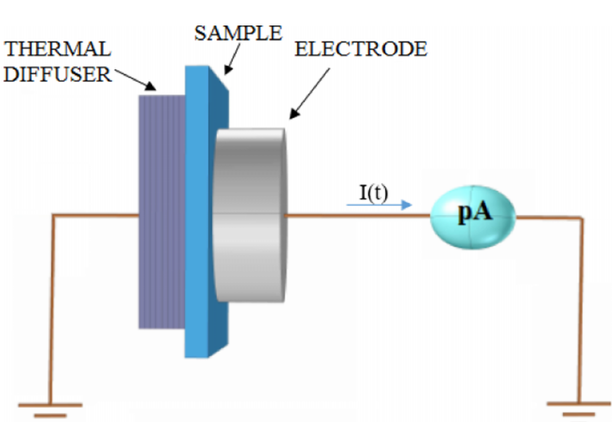

FIG. 3. Test setup of the TSM in short-circuit condition.

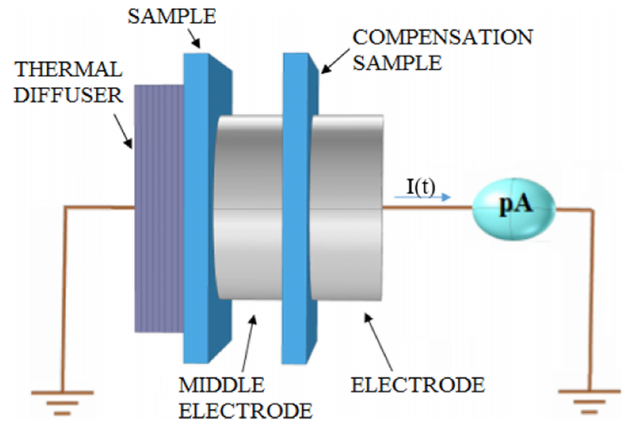

FIG. 4. Test setup of the TSM with double capacitor.

TSM can be also applied to the field of micro- and nanoelectronics. However, this method can be destructive when the investigation concerns layers of material with thicknesses below micrometers, as described in Ref. 42. In order to overcome this problem, the thermal step technique is joined to the capacitance-voltage technique, which is accurately proposed in Refs. 42–44. More in particular, Dagher *et al.*[45] brought the resolution to values between 22 nm (in polymeric materials) and 50 nm (in silicon dioxide) by using an optical instrumentation with laser pulse of the order of femtoseconds. The signal to noise ratio was low, so the method needed further investigations.

An important work has been also carried out by Stancu *et al.*,[46] which analyses the space charge behavior in a low density polyethylene (LDPE) disks of 0.5 mm thickness, with and without water trees. Experimental results have shown that the presence of water trees increases the accumulation of the space charges.

The proposed method has several significant advantages with respect to other methods.[14,40] This is due to the non-destructive nature of the TSM, which is achieved by choosing the value of the maximum temperature imposed by the thermal step equal to the ambient temperature.

A drawback of the proposed technique is related to the thermal contact between the radiator and the sample, which could cause, if imperfect, temperature fluctuations and, therefore, attenuation or delay of the current response. This issue has been mathematically analyzed in Ref. 17.

C. The thermal step method under applied DC field

In year 2000 Agnel *et al.* developed a work finalized to perform measurements under the application of a DC electric field.[18]

However, the scheme of Figure 3 was not completely suitable for the measurements under electric field, because of the use of the current amplifier, as better explained in Refs. 14 and 18.

To overcome this challenge, a compensation sample in front of the specimen was placed, obtaining the so called "double capacitor" configuration, which is represented in Figure 4.[14,40]

In order to measure space charge distribution, the testing procedure requires two steps: first, the high voltage is applied to the middle electrode, while the pA is short circuited. Second, the high voltage is disconnected in order to avoid the carriage of charges through the electrodes, compromising the correct measurement. The space charge can be assessed in the same manner described in Section II B. Further details are given in Refs. 14, 18, and 38.

In 2014, Laurentie *et al.* proposed the "contactless" configuration in order to measure both the space charge inside the dielectric and the surface charge. In this configuration the upper face of the specimen is isolated from the upper electrode through a thin layer of air, avoiding disturbances. The diagram and explanation of the method are provided in Ref. 47.

The spatial resolution, which decreases when the distance between the space charge inside the sample and the electrode in contact with the thermal diffuser increases, is comprised between 50 and 100 μm for a polyethylene terephthalate (PET) sample of thickness of 100 μm.[47]

In order to evaluate the influence of the electric field gradient and temperature in the charges distribution, space charge profiles were carried out in 0.5 mm of a XLPE sample, under different DC electrical stress (from 2 to 60 kV/mm) and temperatures (from 70 to 90 °C). The obtained results have shown that the space charge accumulation grows with the increase of both electric field and temperature.[48]

D. The thermal step method for cables

The thermal step method can also be applied to power cables by using two possible techniques:[49,50]

- The Outer Cooling Technique (OCT)
- The Inner Heating Technique (IHT)

The principle of operation of both techniques does not differ from the method described in Section II B,[51] in which the electrodes are now replaced by the core of cable and outer semicon, while the thermal diffuser is disposed around the cable under test.

The test setup is shown in Ref. 14, and the expression of the output signal $I(t)$ is similar to that of the flat sample configuration (Equation (2)), in which the integral one is extended to the inner and outer rays of the cable insulation, r_0 and r_i, respectively, as reported in the following equation:[51,52]

$$I(t) = -\alpha C \int_{r0}^{ri} E(r) \frac{\partial \Delta T(r,t)}{\partial t} dr. \qquad (4)$$

The work in Ref. 52 shows how to determine the electric field and the space charge profiles. In addition, the work in Ref. 53 demonstrates that the resolution of the method is in the order of millimeters and typically smaller than 20 mm.

As well as for the flat specimens discussed in Section II B, a similar experiment was done in order to evaluate the effect of water trees on space charge accumulation in 50 cm and 70 m long cable specimens.[54] The smaller sample has been tested by using the OCT (a thermal step of −30 °C), while the longer one was studied using IHT. The presence of water trees, as for flat specimens, results in a greater accumulation of charge for both samples.

The described method has been also developed for on-site applications, by using power DC/DC converters for the control of high currents circulating in the inductor wrapped on the cable.[55]

The TSM has been applied by Mazzanti *et al.* to the cables during both pre-qualification and type tests.[56]

The same article reports the most relevant problems related to this method. A relevant challenge for this method can be identified by the significant space occupied by the test setup, which is also composed by an additional cable (namely "compensation cable"), identical to the cable under measurement and connected to its terminals, in order to avoid the problems related to the current amplifier, as described in Section II C. Another problem consists in the test procedure, because before the space charges measurement the DC source must be disconnected, while the cold liquid must begin to flow. This fact involves longer times between two subsequent measurements, when compared to other techniques, such as the Pulsed Electro Acoustic (PEA) method.[13]

E. Alternative thermal wave method (ATWM)

The ATWM was developed by Reboul *et al.* in 2001 for measurements on thin dielectrics located in power capacitors.[57] The main difference between the TSM is that employed to have a better resolution using a thermal excitation over a long period of time rather than a single stimulus.[58] As a matter of fact, the thermal excitation brought by the radiating electrode does not give sufficient resolving power for the space charge measurement in thin dielectric films (due to a high number of information lost during the beginning of the transient current). The resolving power can be improved by using a long periodic thermal excitation.[59]

With this method, a resolution of a few μm is obtained, and a wide range of thicknesses can be analyzed, from 50 μm up to 3 mm.

The ATWM is used in order to measure the space charge profiles, while another technique, called Thermal Stimulated Discharge Current (TSDC), can be used to study the injection, transport, and trapping of charges. By considering this aspect, in Ref. 59 these two techniques have been applied simultaneously in order to carry out a complete study of space charge behavior.

In 2011, the ATWM was improved in terms of accuracy by applying two simultaneous thermal waves in both surfaces of the specimen.[60]

F. Laser intensity modulation method

The laser intensity modulation method was invented by Lang and Das-Gupta during the mid-1980s.[61,62] Lang is also the author of a review article regarding the LIMM method,[20] with data updated to 2003.

The phenomenon of polarization is investigated in Ref. 20, in which the difficulties of the currently experimental data analysis that resides in this method are highlighted, due to an ill-posed problem with multiple solutions. The solution of this problem is reported in the same article through the introduction of the Polynomial Regularization Method, PRM. The space charge phenomenon with the LIMM method is studied in Refs. 19, 43, and 63.

Generally, in the LIMM method the metalized surfaces of a specimen are heated by using a laser with modulated sinusoidal intensity in time, as shown in Figure 5. Thus, a non-uniform distribution of the temperature is produced along the thickness of the sample. The laser beam is absorbed by the electrode, and its sinusoidal modulation causes a sinusoidal fluctuation of the temperature in the electrode.

Consequentially, a temperature wave is diffused within the sample and attenuated and delayed in phase. In this way, an unevenly distributed thermal force is displayed over the sample. Therefore, the interaction between this force and the space charge generates a sinusoidal pyroelectric current,[14] which can be written by the following expression:

$$I(t) = \frac{S}{d}\int_0^x G(x)\frac{\partial \Delta T(x,t)}{\partial t}dx, \tag{5}$$

where S and d are the area and the thickness of the sample, respectively, T is the temperature, and $G(x)$ is the distribution function.

As well as for the methods described in Secs. II A–II E, several deconvolution techniques have been developed during the years, finalized to determine both the space charge and the polarization distributions.[64,65]

This technique has been applied to many application fields, from measurements in the dielectric used in spatial applications[66,67] to measurements of XLPE specimens,[64,68,69] with a resolution between 1 and 2 μm.

G. Focused laser intensity modulation method

In order to carry out 3D measurements starting from the LIMM method, Marty-Dessus *et al.* developed the focused laser intensity modulation method, also named Focused LIMM (FLIMM).[70] The principle of operation has remained unchanged with respect to the LIMM technique. However, as shown in Figure 6, which schematically represents the test setup of this method, the three dimensional distributions of the space charge are obtained by moving the laser beam generated by the laser diode in the two directions z-y. The measure along the z-direction, which corresponds to the thickness direction, depends on the laser beam modulation frequency. The output current signal of the system, $I(f)$, is given by the following equation:

$$I(f) = \frac{A}{L}j2\pi \cdot f\int_0^L k(x)T(x,f)dz, \tag{6}$$

where A is the cross-sectional area of laser beam, L is the specimen thickness, T is the temperature, and k is the generalized pyroelectric coefficient.

In Ref. 24 the proposed method was compared with the thermal pulse method (TPT) in order to determine the three-dimensional polarization distributions in poly (vinylidenefluoride-trifluoroethylene) (PVDF-TrFE) film. The carried out tests have shown that the TPT gives very good and fast results, while the FLIMM was characterized with a better lateral resolution.

In further works,[71,72] the FLIMM technique was compared with the PEA method.[73]

Furthermore, the works proposed in Refs. 74 and 75 put in evidence the relationship occurring between the space charge measured by the FLIMM technique and the induced mechanical deformation, which was measured with the DIC (Digital Images Correlation) technique.

The FLIMM technique was used for thicknesses up to μm and resolutions in the lateral direction and in the axial direction of few μm and about 1 μm, respectively.[74,75] The range of these parameters was depending on both the amplitude of the laser beam and the mathematical method used.[70]

Marty-Dessus and other researchers have recently modified the FLIMM method by creating an air gap between the upper measuring electrode and the related sample.[76] Their first

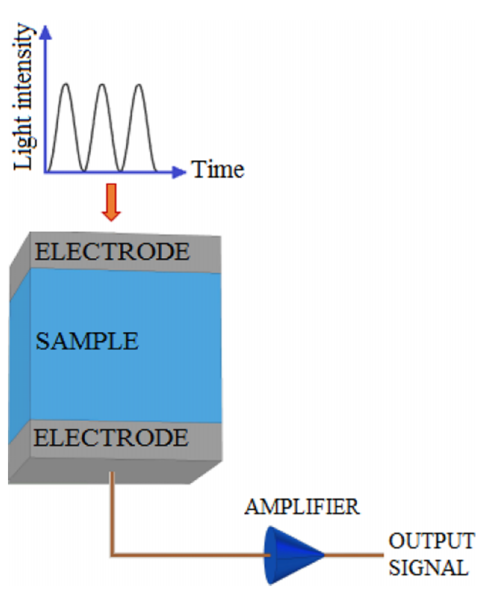

FIG. 5. Working principle of the LIMM method test setup.

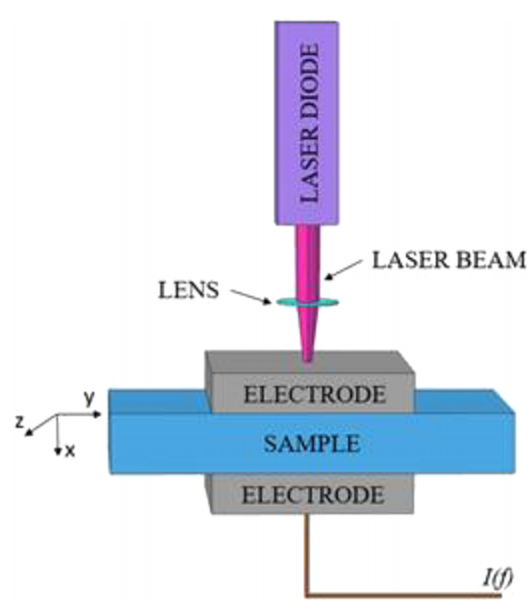

FIG. 6. Test setup of the FLIMM method.

experiment has involved the 2D and 3D cartography of the space charge carried out in polar PVDF (Polyvinylidenefluoride) and electron irradiated PTFE (Polytetrafluoroethylene) samples.

III. CONCLUSIONS

Space charge measurements have been highly attractive for many researchers. During the years, various non-destructive measuring methods have been developed, and, in particular, thermal methods have been widely used both to test flat specimen and full-size cables.

All the techniques discussed in this paper have the problem linked to the difficult interpretation of the output signal. For this purpose, a mathematical treatment of voltage or current carried out in the different methods was needed.

As regard to the applications, the most widely used method is the TSM, which is relatively suitable for cable specimens, in which the space charge distributions are carried out also with an applied DC field.

Finally, from a general scientific point of view, it is worthwhile to mention here that we found several methodological research approaches similar to those developed in the field of space charge phenomenon we had applied in different research activities.[77–100]

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