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Edition 1.0 2020-11

# TECHNICAL SPECIFICATION



## Measurement of internal electric field in insulating materials – Pressure wave propagation method



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# MEASUREMENT OF INTERNAL ELECTRIC FIELD IN INSULATING MATERIALS – PRESSURE WAVE PROPAGATION METHOD

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This first edition of IEC/TS 62836 cancels and replaces the first edition of the Technical Report of IEC/TR 62836 published in 2013. It constitutes a technical revision.

The text of this Technical Specification is based on the following documents:

| Draft | Report on voting |
|---|---|
| 112/472/DTS | 112/499/RVDTS |

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Specification is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

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- withdrawn,
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# INTRODUCTION

High voltage insulating cables, especially high voltage DC cables, are subject to charge accumulation and this may lead to electrical breakdown if the electric field produced by the charges exceeds the electrical breakdown threshold. With the trend to multiply power plants, especially green power plants such as wind or solar generators, more cables will be used for connecting these power plants to the grid and share the electric energy between countries. Therefore, the materials for the cables, and even the structure of these cables, when considering electrodes or the junction between cables, need a standardized procedure for testing how the internal electric field can be characterized. The measurement of the internal electric field would give a tool for comparing materials and help to establish thresholds on the internal electric field for high voltage applications in order to limit breakdown risks as much as possible. The pressure wave propagation (PWP) method has been used by many researchers to measure the space charge distribution and the internal electric field distribution in insulators. However, since experimental equipment, with slight differences, is developed independently by researchers throughout the world, it is difficult to compare the measurement results between the different equipment.

The procedure outlined in this Technical Specification provides a reliable point of comparison between different test results carried out by different laboratories in order to avoid interpretation errors. The IEC has established a project team to develop a procedure for the measurement of PWP.

# MEASUREMENT OF INTERNAL ELECTRIC FIELD IN INSULATING MATERIALS – PRESSURE WAVE PROPAGATION METHOD

## 1 Scope

This document provides an efficient and reliable procedure to test the internal electric field in the insulating materials used for high-voltage applications, using the pressure wave propagation (PWP) method. It is suitable for a sample with homogeneous insulating materials and an electric field higher than 1 kV/mm, but it is also dependent on the thickness of the sample and the pressure wave generator.

## 2 Normative references

There are no normative references in this document.

## 3 Terms, definitions and abbreviated terms

For the purposes of this document, the following terms, definitions and abbreviated terms apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

### 3.1 Terms and definitions

**3.1.1**
**pressure wave propagation**
PWP
pressure wave that is propagated in a material containing electric charges and measurement of the induced electric signal from electrodes

### 3.2 Abbreviated terms

| | |
|---|---|
| CB | carbon black |
| EVA | ethylene-vinyl acetate |
| LDPE | low density polyethylene |
| LIPP | laser induced pressure pulse |
| PE | polyethylene |
| PIPP | piezoelectric induced pressure pulse |
| PMMA | poly (methyl methacrylate) |
| PWP | pressure wave propagation |
| S/N | signal to noise ratio |

## 4 Principle of the method

The principle of the PWP method is shown schematically in Figure 1.

The space charge in the dielectric and the interface charge are forced to move by the action of a pressure wave. The charge displacement then induces an electrical signal in the circuit which is an image of the charge distribution in short-circuit current measurement conditions. The expression for the short-circuit current signal with time $t$ is

$$i(t) = C_0 \int_0^d BE(x) \frac{\partial p(x, t)}{\partial t} dx \, , \quad (1)$$

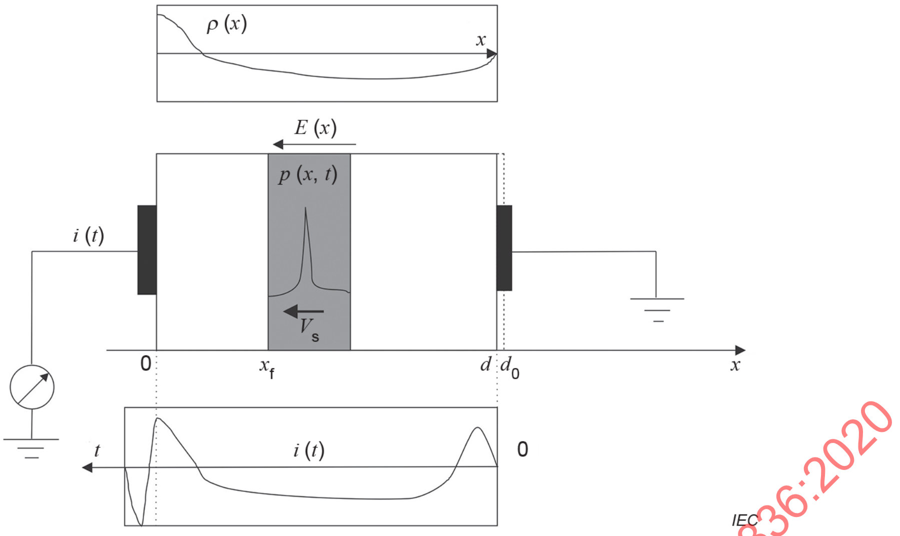
where

| | |
|---|---|
| $E(x)$ | is the electric field distribution in the sample at position $x$; |
| $d$ | is the thickness of sample; |
| $p(x, t)$ | is the pressure wave in the sample, which depends on the electrode materials, dielectric sample material, the condition of coupling on the interface, etc.; |
| $C_0$ | is the sample capacitance without the action of a pressure wave. |

$C_0$ depends on the thickness of the sample, and its surface area which is equal to the area of action of the pressure wave.

The constant $B = \chi(1 - a/\varepsilon)$ only depends on the characteristics of the dielectric materials. In this formula, $\chi$ is the coefficient of compressibility of the material, $\varepsilon$ is the permittivity of the material and $a$ is the coefficient of electrostriction of the material. For heterogeneous dielectric materials, $B$ is a function of space. For homogeneous dielectric materials, $B$ is not a function of space and can be put outside of the integral. In this proposition, only homogeneous dielectric materials are considered, so $B$ is a constant.

In Equation (1), the electric field distribution can be obtained if it is deconvolved.



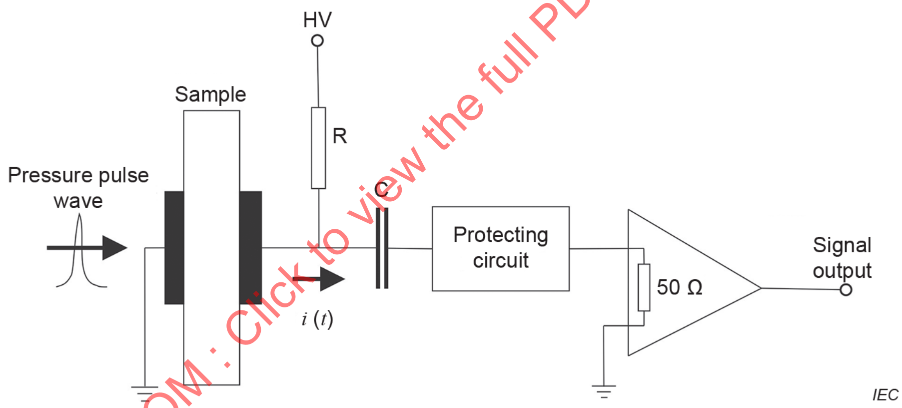

**Key**

$x_f$ is the position of pulse front

$d_0$ is the original thickness of sample

$d_0 \approx d$ in the case of a narrow pulse

**a) Applied pressure pulse and measured short-circuit current signal**




**b) Measuring schematics**

**Figure 1 – Principle of the PWP method**

The applied pressure wave can be generated by different techniques, but the same kind of analysis can be done for any of these techniques. The main practical PWP method can be divided into two ways: a pressure pulse is induced by a powerful laser pulse, a technique called LIPP method, and a pressure pulse generated by a piezoelectric device, a technique called PIPP. The sensibility and resolution of the PWP method depends mainly on the amplitude and width of the pressure pulse. The advantage of the LIPP method is to produce highly sensitive measurements without contact. The advantage of the PIPP method is to obtain the measurement with a high measuring rate and allow a cost measurement system.

In the case of a narrow pulse, for example when the width of the pressure pulse is much smaller than the thickness of the sample, $\tau$ is the pressure pulse duration with $\tau << \left[\min\left(d_0, d_x\right)\right] / v_s$,

$$\begin{cases} \int_0^t i(t')dt' = C_0 B\overline{E(x)}\int_0^d p(x,\ t)dx \\ x = v_s t \end{cases}, \tag{2}$$

where

$v_s$ is the sound speed in the sample;

$\overline{E(x)},\ x = v_s t$ is the mean electric field during the pressure pulse width at the position $x$. For simplicity, it is shown as $\overline{E(x = v_s t)}$ in this document.

Because of sound loss and sound dispersion in polymer dielectrics, the amplitude of $p(x,t)$ will decrease, and the width of $p(x,t)$ will increase during the propagation of a pressure pulse in the sample. For polymer dielectrics, the sound dispersion is dominant, therefore, even if $p(x,t)$ is not a constant in the dielectrics, its integral $\int_0^d p(x,t)dx$ remains constant during its propagation in the sample.

From the Equation (2) and from the signal obtained with a sample free of charges and submitted to an intermediate voltage $V_0$, $B\int_0^d p(x,t)dx$ can be obtained since the electric field $\overline{E(x = v_s t)} = E_0$ is uniform in this case and the sample capacitance $C_0$ is directly proportional to the thickness of the sample. This can be used as a calibration base for the other measurements.



## 5 Samples

A dielectric insulating material is suggested, for example polyethylene, with a thickness of 1 mm or 2 mm planar plaque sample with a diameter sufficiently large to avoid edge discharges, typically larger than 20 cm with 5 cm centred electrodes for 60 kV.

## 6 Electrode materials

The selection of electrode materials depends on the method of the generation of the pressure pulse wave. Usually, semi-conductive electrodes with ethylene-vinyl acetate (EVA) + carbon black (CB) or polyethylene (PE) + carbon black (CB) are used. For laser PWP (also called LIPP), the suitable thickness of the semi-conductive electrode is about 0,5 mm, and it shall be less than 1 mm. If different materials are used for the electrode and the insulator, the transit time of the pressure wave through the electrode should be at least half the one in the insulator to avoid spurious echoes.

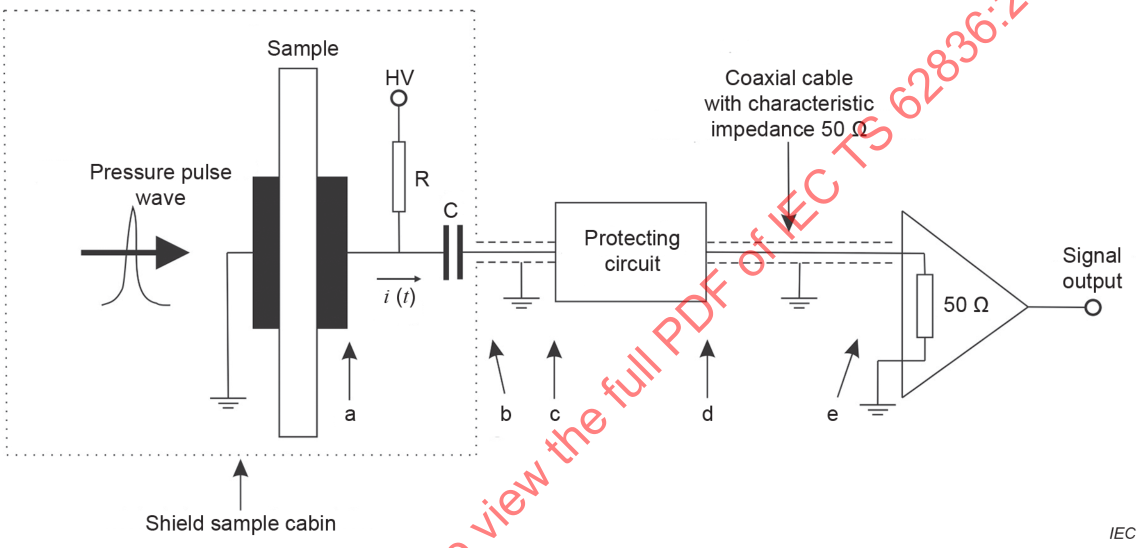
It is important to keep good contact between the electrode and the insulator. It is recommended to use the hot-press method for marking the electrode on the sample.

## 7 Pressure pulse wave generation

The suggested pressure pulse wave should have a 20 ns to 50 ns duration, and a 1 MPa to 10 MPa amplitude. It can be produced by a piezoelectric driven device, or by a powerful pulsed laser. If a powerful laser is used, the suggested energy is about 300 mJ to 500 mJ per pulse with a 3 ns to 7 ns duration.

## 8 Set-up of the measurement

The practical set-up of the measurement is shown in Figure 2. In the practical set-up, the length $l_{ab}$ (the length of the connection between the sample and the output connector) shall be less than 0,5 m. The length $l_{bc}$ of the connection cable with the characteristic impedance of 50 Ω between the output and the protecting circuit (between b and c) should be less than 0,5 m. The length $l_{de}$ of the connection cable with the characteristic impedance of 50 Ω between the protecting circuit and the amplifier (between d and e) should be less than 0,5 m. The total length of $l_{bc} + l_{de}$ (between b and e) should be less than 0,5 m too. This is the principal suggestion to avoid any reflection effect of the measured signal between the amplifier and the sample, in the case where the input impedance of the amplifier is not the perfect match with the signal cable. An amplifier with a 40 dB and 200 MHz bandwidth is suitable. The input impedance of the amplifier should be strictly 50 Ω to avoid the unwanted reflecting signal.




**Key**

a, b, c and d indicate the real positions in the measuring system

**Figure 2 – Measurement set-up for the PWP method**

The practical protecting circuit is shown in Figure 3. Diodes in the protecting circuit should have a fast recovery time to overcome a quick overvoltage. It is recommended to use a 5 Ω resistor without residual induction in the protecting circuit.

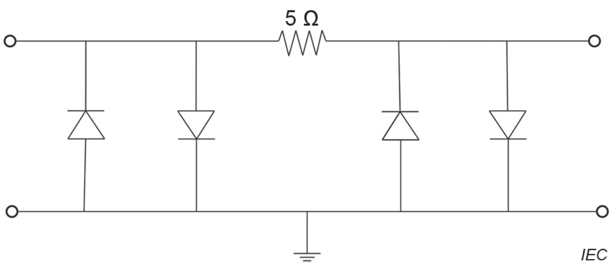



**Figure 3 – Sample of circuit to protect the amplifier from damage by a small discharge on the sample**

## 9 Calibrating the electric field

For a planar sample with a thickness of 1 mm to 2 mm, the applied field for calibration is about 5 kV/mm to 10 kV/mm during a short period of time (typically less than 10 s) in order to avoid space charge injection and accumulation. If space charges already exist in the sample prior to the calibration measurement, it is possible to construct the calibration measurement from a measurement under voltage as explained before and to subtract from it the signal measured under short-circuit just before or just after the measurement under voltage.

## 10 Measurement procedure

To implement the same dielectric insulating materials, the same electrode materials, and the same interface condition between the electrode and insulator, one sample with a thickness $d_0$ is used as the calibrating sample, and another sample with a thickness $d_x$ is used as the testing sample.

For the calibrating sample with the thickness $d_0$, voltage $V_0$ is applied during a short period of time that is quick enough to not induce space charge accumulation in the sample. The internal electric field in the sample is $E_0 = -V_0 / d_0$ in the absence of space charge. With the action of the pressure pulse wave, the measured short-circuit current signal will be

$$i_c(t) = C_0 B \int_0^{d_0} E_0 \frac{\partial p(x,t)}{\partial t} dx . \tag{3}$$

Applying an integration over time on this current signal, one obtains

$$\int_0^t i_c(t')dt' = C_0 B E_0 \int_0^{d_0} p(x, t)dx \tag{4}$$

where, $\overline{E} = E_0$ since the electric field is uniform.

For the testing sample with the thickness $d_x$, the measured short-circuit signal is

$$i_m(t) = C_0 B \int_0^{d_x} E(x) \frac{\partial p(x, t)}{\partial t} dx \tag{5}$$

Now, the internal electric field depends on the applied voltage and space charge. It is therefore no longer a uniform field but varies as a function of the space position. After integration over time, one has

$$\int_0^t i_m(t')dt' = C_x B \overline{E(x = v_s t)} \int_0^{d_x} p(x,t)dx . \tag{6}$$

## 11 Data processing for the experimental measurement

The integral of the pressure pulse is the same for the testing sample and for the calibrating sample, i.e.

$$\int_0^{d_0} p(x,\ t)dx = \int_0^{d_x} p(x,\ t)dx \tag{7}$$

If the active area of the pressure pulse is $S_0$, then

$$C_0 = \frac{\epsilon_0 \epsilon_r S_0}{d_0},\quad C_x = \frac{\epsilon_0 \epsilon_r S_0}{d_x},\quad E_0 = -\frac{V_0}{d_0} \tag{8}$$

So, one has

$$\frac{\int_0^t i_\mathrm{m}(t')dt'}{\int_0^t i_\mathrm{c}(t')dt'} = \frac{\frac{\varepsilon_0 \varepsilon_r S_0}{d_x} B\overline{E(x=v_\mathrm{s}t)} \int_0^{d_x} p(x,\ t)dx}{-\frac{\varepsilon_0 \varepsilon_r S_0}{d_0} B \frac{V_0}{d_0} \int_0^{d_0} p(x,\ t)dx} = \frac{-d_0 \overline{E(x=v_\mathrm{s}t)} d_0}{d_x V_0}. \tag{9}$$

The following can be obtained

$$\overline{E(x=v_\mathrm{s}t)} = -\frac{\int_0^t i_\mathrm{m}(t')dt'}{\int_0^t i_\mathrm{c}(t')dt'} \times \frac{d_x V_0}{d_0^2}. \tag{10}$$

If the thickness and tested area are equal for the testing sample and for the calibrating sample, or if the testing sample is also used as the calibrating sample $d_0 = d_x$

$$\overline{E(x=v_\mathrm{s}t)} = -\frac{V_0}{d_0} \times \frac{\int_0^t i_\mathrm{m}(t')dt'}{\int_0^t i_\mathrm{c}(t')dt'} = E_0 \times \frac{\int_0^t i_\mathrm{m}(t')dt'}{\int_0^t i_\mathrm{c}(t')dt'}. \tag{11}$$

Therefore, the internal electric field can be obtained from the above Equation (11). The method is suitable both for the sample under voltage and for the sample in short-circuit containing space charge.

It can be noticed that the denominator of that expression should be a constant since the electric field is uniform in the case of the calibration measurement. In order to improve signal to noise ratio, the denominator can be safely replaced by the amplitude of the integral once calculated, or by the integral of the first peak as

$$\overline{E(x=v_\mathrm{s}t)} = -\frac{V_0}{d_0} \times \frac{\int_0^t i_\mathrm{m}(t')dt'}{\int_0^{5\tau} i_\mathrm{c}(t')dt'} = E_0 \times \frac{\int_0^t i_\mathrm{m}(t')dt'}{\int_0^{5\tau} i_\mathrm{c}(t')dt'} \tag{12}$$

In this Equation (12), $\tau$ is the duration of the pressure pulse in the sample, the denominator of the equation is no longer a function of time, but the definite integral of the first peak of the measured current. The upper limit of the integral is set to $5\tau$ to ensure that the first peak of current is completely included. The upper limit can be adjusted according to the conditions.

## 12 Measurement examples

### 12.1 Samples

A low density polyethylene (LDPE) plaque sample with a 1,16 mm thickness and a 20 cm diameter is used. The EVA+CB electrodes with a 0,6 mm thickness and a 5 cm diameter are attached on the LDPE sample by hot-press. In this example, the calibrating sample and testing sample are the same sample.

### 12.2 Pressure pulse generation

A laser pulse with a 500 mJ energy and 6 ns duration produced by a Nd:YAG pulsed laser, radiates on the EVA+CB electrode directly. It introduces the pressure pulse wave in the sample by the plasma ablation on the electrode surface. Since the acoustic impedance is very similar for the LDPE sample and for the EVA+CB electrode, the reflection on the interface between LDPE and EVA+CB can be ignored.

### 12.3 Calibration of sample and signal

Measurements and calibration should be done at the same temperature depending on the materials and their application. Here, it is recommended to set the experiments at 40 ºC but not at room temperature, because room temperature may fluctuate. Under the temperature of 40 °C, a relatively low voltage (−5,8 kV) is applied to the sample. The signal is measured shortly after the application of the voltage, for example within 1 min. The internal electric field is 5 kV/mm for this sample. Knowing the sample thickness and the transit time, which can be determined by the time between the beginnings of two peaks, the sound velocity can be obtained from the measured signal, $v_s$ = 2 017 m/s.



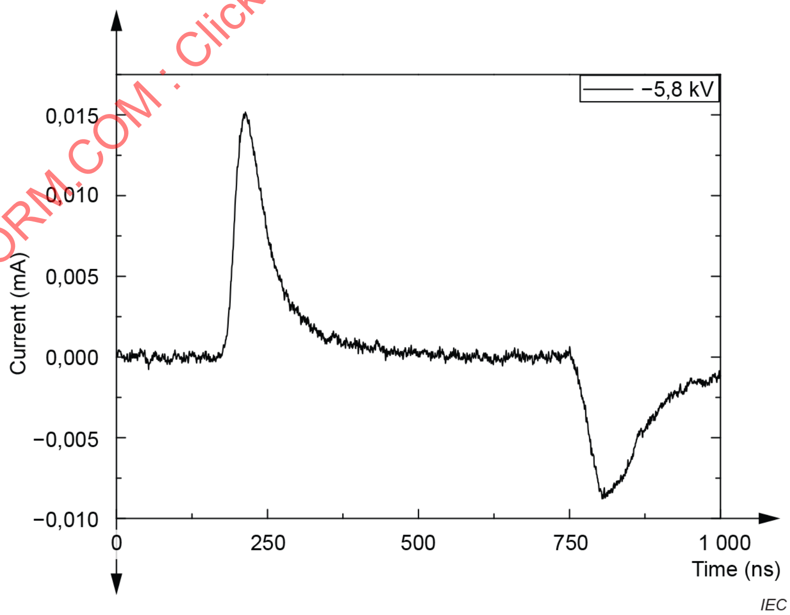



**Figure 4 – Measured current signal under –5,8 kV**

The preconditional method of the original signal can be found in Annex A. The linearity verification of the measuring system can be done at any time if it is necessary, or within a certain period, for example one year at least. The method for the linearity verification can be found in Annex B.

### 12.4 Testing sample and experimental results

Under the same temperature, a relative high voltage (–46,4 kV) is applied to the same sample for 1,5 h. The evolution of the signal is measured. The applied internal electric field is 40 kV/mm (see Figure 5 to Figure 7).

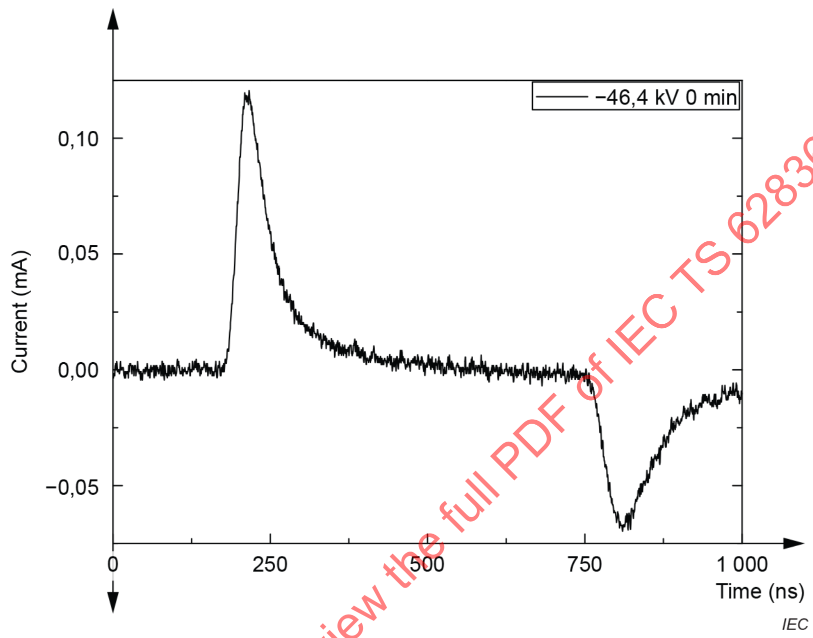



**Figure 5 – First measured current signal (< 1 min)**

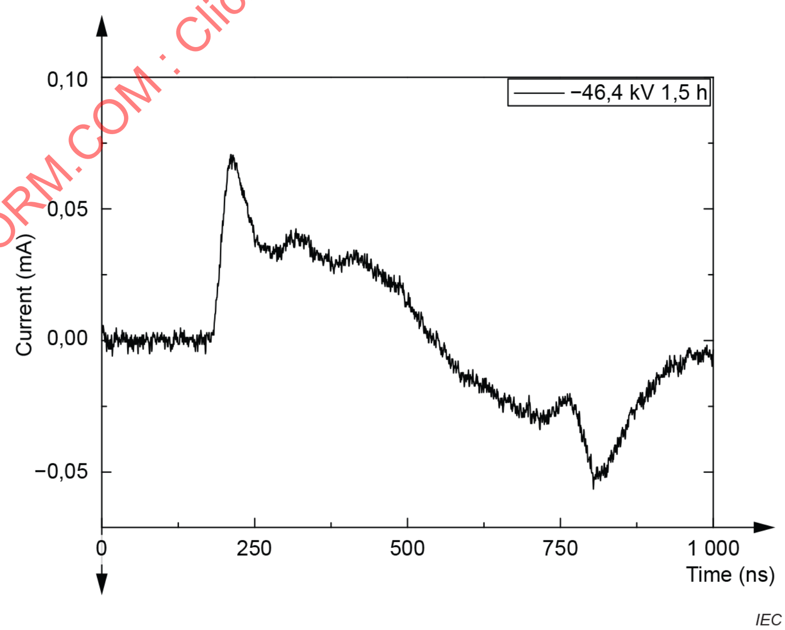



**Figure 6 – Measured current signal under –46,4 kV, after 1,5 h under high voltage**

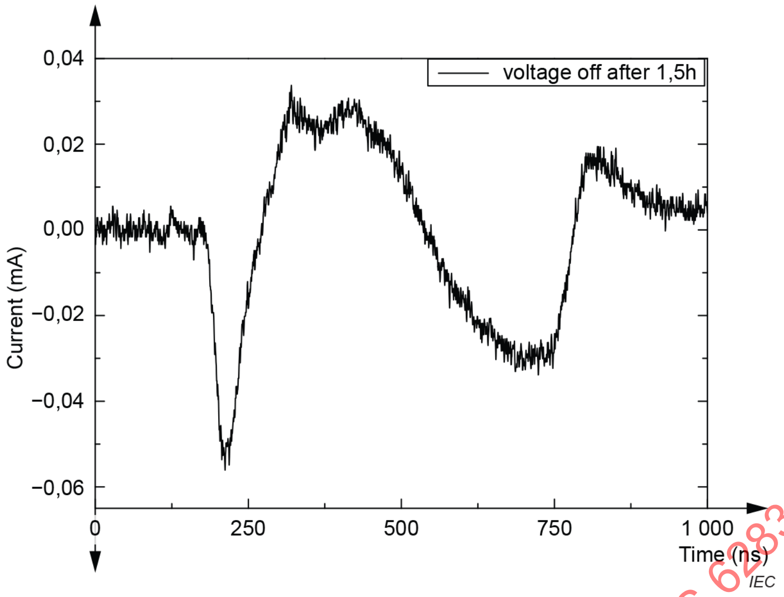



**Figure 7 – Measured current signal without applied voltage, after 1,5 h under high voltage**



For this sample, at the beginning of the applied voltage, there is no space charge in the sample but only charges on the electrodes. After a while, there are space charges injected from both electrodes inside the sample. When the voltage is switched-off (Figure 7), certain space charges remain in the insulating material and also charges on the electrodes adapted to the short-circuit condition across the sample.

Figure 8 to Figure 11 show the electric field distribution for the various voltages.

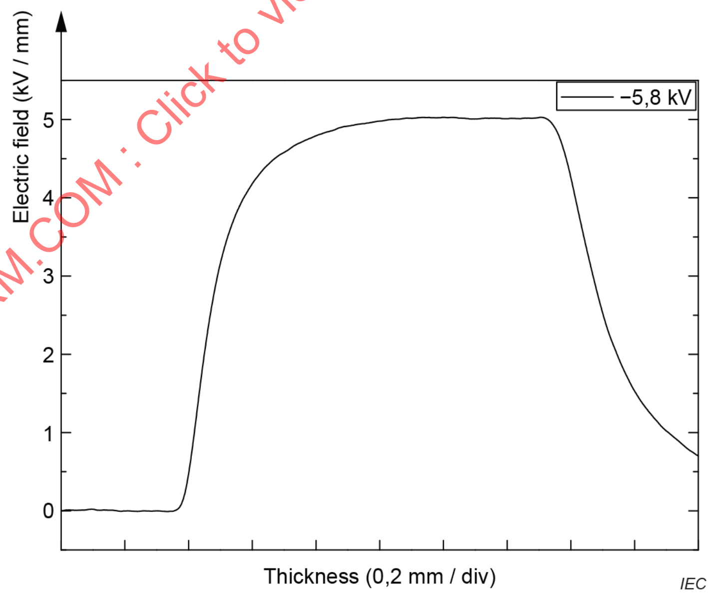



**Figure 8 – Internal electric field distribution under –5,8 kV**

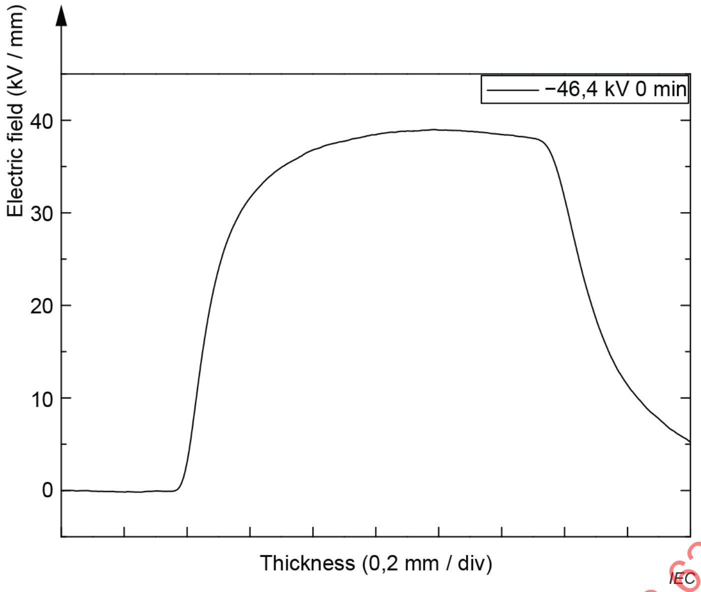



**Figure 9 – Internal electric field distribution under –46,4 kV, at the initial state**

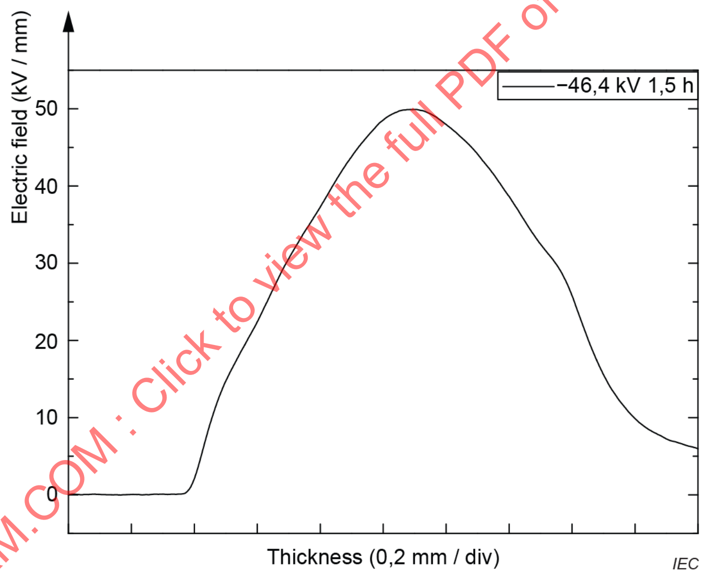



**Figure 10 – Internal electric field distribution under –46,4 kV, after 1,5 h under high voltage**

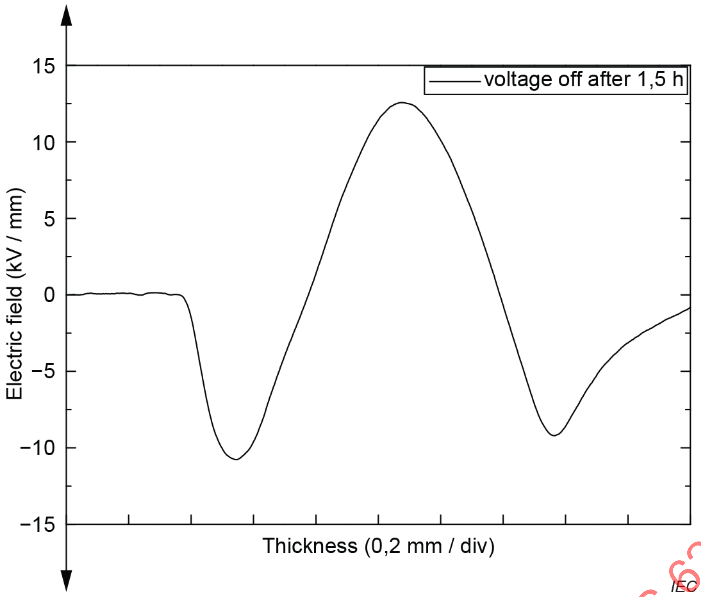



**Figure 11 – Internal electric field distribution without applied voltage after 1,5 h under high voltage**

From the raw measurements (Figure 4 to Figure 7), signals are processed according to the treatments described in Equation (12) into Figure 8 and Figure 9. There is no space charge in the sample and the electric field is uniform, i.e. it is dependent on the applied voltage divided by the thickness of the sample. In Figure 10, the injected charges under the applied voltage modify the field distribution with a large amount in the middle of the sample. Without the applied voltage (Figure 11), the distribution of the electric field in the middle of the sample is still large due to the presence of space charge in the sample.

# Annex A
(informative)

# Preconditional method of the original signal for the PWP method

## A.1 Simple integration limitation

It is known that integration procedures suffer from the presence of offsets of the original signal. Indeed, the integration of an offset leads to a drift that can be erroneously interpreted. For that purpose, the offset of any measured signals shall be removed before implementing an integration. In the case of the laser PWP method, due to the relaxation of target material, some targets that are used to convert the laser pulse to the pressure pulse show a resiliency resulting in a non-zero pressure amplitude after the pulse, as illustrated in Figure A.1. That is the case of the carbon loaded EVA target as shown in Figure A.2.

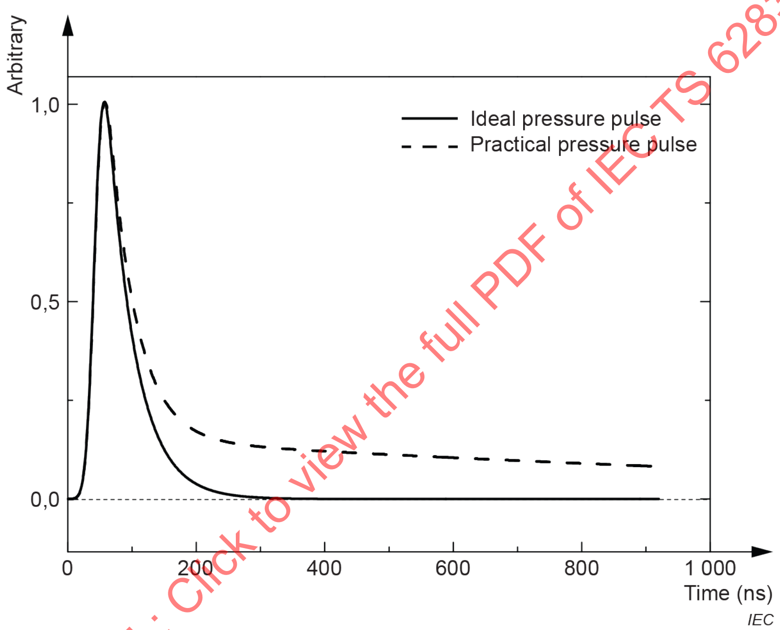



**Figure A.1 – Comparison between practical and perfect pressure pulses**

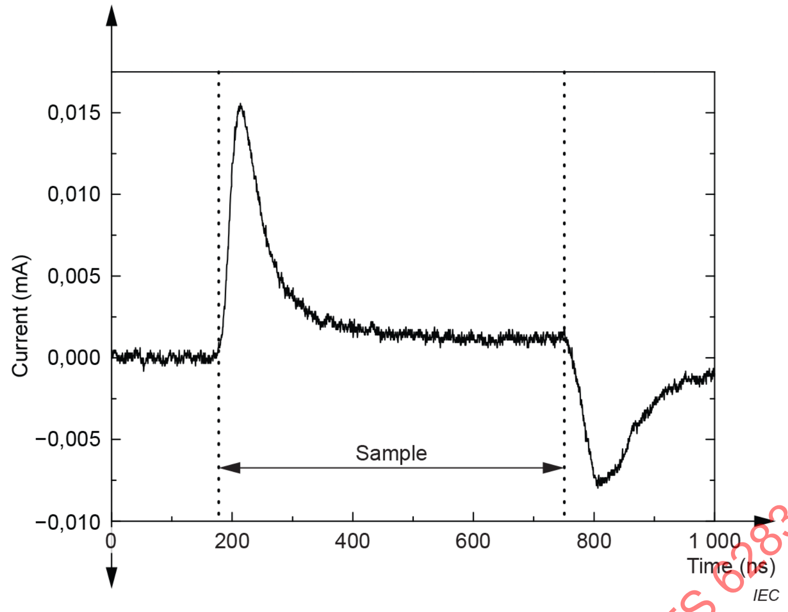



**Figure A.2 – Original signal of the sample free of charge under moderate voltage**



Though the resiliency effect is partially corrected by the procedure described in this document, an improved integration procedure can be used to obtain better electric field estimations. This improved integration procedure includes a correction of the laser-generated pressure pulse so as to remove the effect of resiliency.

## A.2 Analysis of the resiliency effect and correction procedure

If the response of the target were perfect, the laser-generated pressure pulse would be an ideal pulse $p(t)$. In terms of linear systems, one can say that the impulse response of the target would be a Dirac function: $\delta(t)$. Due to resiliency, the response of the target includes a slow process governed by an exponential law. Therefore, in addition to the ideal pulse $p(t)$, one obtains a slow decreasing offset. In terms of linear systems, one can say that the practical impulse response of the target is the sum of a Dirac and an exponential function: $\delta(t)+Ae^{-at}H(t)$, where $A$ is the amplitude of the resiliency effect, $1/a$ is its time constant and $H(t)$ is the Heaviside function. In the Laplace space, the practical target transfer function is

$$F(s)=1+\frac{A}{s+a}=\frac{s+a+A}{s+a}. \tag{A.1}$$

The correction of the resiliency effect consists in compensating the dependence on $s$ of the practical target transfer function. This can be done by multiplying the practical target transfer function with $1/F(s)=(s+a)/(s+a+A)$. Its inverse Laplace transform is

$$L^{-1}\left[\frac{1}{F(s)}\right]=\delta(t)-Ae^{-(a+A)\,t}\;H(t) \tag{A.2}$$

where $L^{-1}$ represents an operation of inverse Laplace transform.

The resiliency can then be corrected by the convolution of the measured signal with Formula (A.2). Since the integration corresponds to a division by $s$ in the Laplace space, the correction and the integration can be performed at the same time. The inverse Laplace transform of $(s+a)/(s+a+A)/s$ is

$$h(t)=\left(1-\frac{A}{a+A}\left(1-e^{-(a+A)\,t}\right)\right)H(t). \tag{A.3}$$

Therefore, the resiliency correction and the integration of the measured signal can be performed at the same time by the convolution of the measured signal with the function $h(t)$. It can be noticed that the first 1 in the parentheses corresponds to the simple integration. The other term except the first 1 in the parentheses corresponds to the resiliency correction.

## A.3 Example of the correction procedure on a PE sample

The original reference signal is measured under a moderate electric field: 5 kV/mm. The peak of the original signal with noise has an obvious resiliency, as shown in Figure A.2. Figure A.3 shows the comparison between the original reference signal and the reference signal corrected by Formula (A.2). The corrected signal was obtained with coefficient $1/A = 537$ ns and $1/a = 1452$ ns

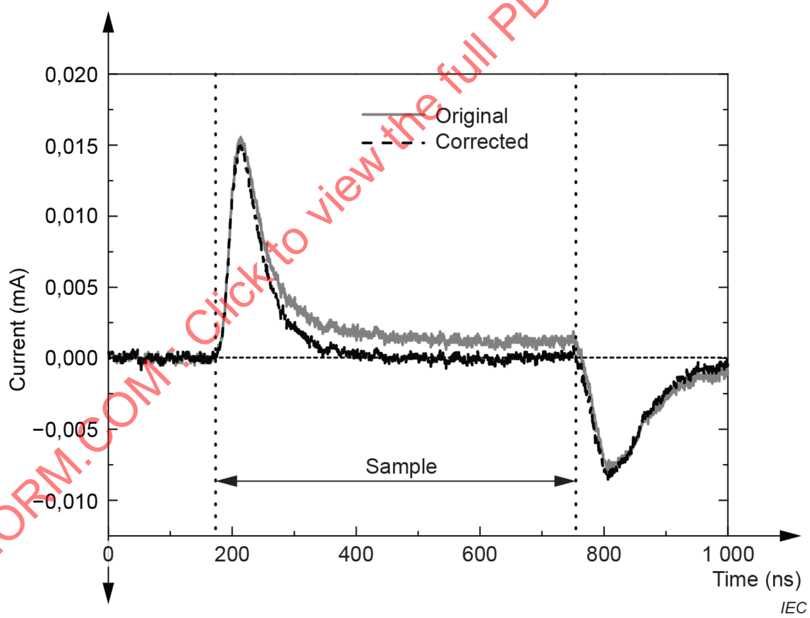





**Figure A.3 – Comparison between original and corrected reference signals with a sample free of charge under moderate voltage**

The signal of the sample with space charge can be corrected and integrated at the same time with $h(t)$, taking the same coefficients as the reference signal. Applying the calibration described in this document leads to the results shown in Figure A.4 for both simple integration and corrected integration.

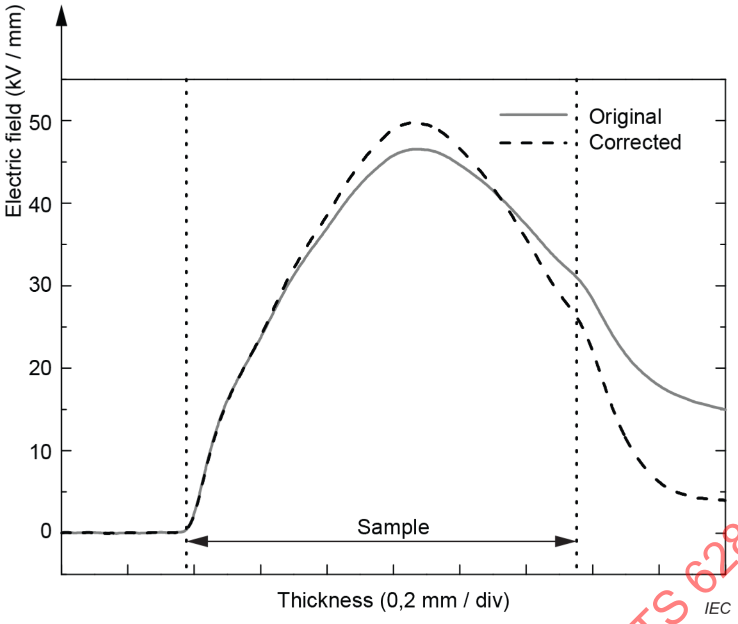



**Figure A.4 – Electric field in a sample under voltage with space charge calculated from original and corrected signals**



Though resiliency introduces a drift with the simple integration procedure, the drift is partially compensated in the sample with the calibration (see 12.3) described in this document. However, the corrected integration procedure gives more accurate results.

## A.4 Estimation of the correction coefficients

Coefficient $a$ and $A$ in Formulae (A.1), (A.2) and (A.3) can be calculated from the geometrical characteristics of the reference signal (see Figure A.5). If $A_{\mathrm{m}}$ and $t_{\mathrm{m}}$ are respectively the amplitude and time of the maximum of the peak, the resiliency after $t_{\mathrm{m}}+2T_{\mathrm{p}}$ can be fitted by the linear function $q(t)$,

$$q(t)=A_{\mathrm{r}}-a_{\mathrm{r}}\left(t-t_{\mathrm{m}}\right), \qquad \text{(A.4)}$$

where $A_{\mathrm{r}}$ is the amplitude at time $t=t_{\mathrm{m}}$ with slope $-a_{\mathrm{r}}$ and the width of the pulse $T_{\mathrm{p}}$ at the amplitude $A_{\mathrm{m}}/2+A_{\mathrm{r}}/4$. Then one has

$$A=\frac{2A_{\mathrm{r}}}{\left(2A_{\mathrm{m}}-A_{\mathrm{r}}\right)T_{\mathrm{p}}} \text{ and } a=\frac{a_{\mathrm{r}}}{A_{\mathrm{r}}}. \qquad \text{(A.5)}$$

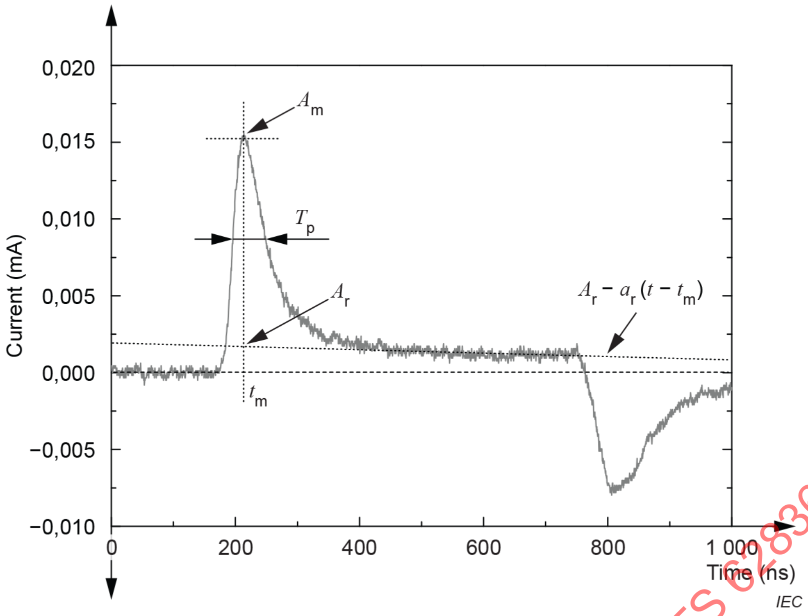



**Figure A.5 – Geometrical characteristics of the reference signal for the correction coefficient estimation**

In the case of the signal presented in Figure A.3, one finds:

$$A_m = 3{,}05\ (\mu A),\quad A_r = 0{,}31(\mu A),\quad \frac{1}{a_r} = 4670\,(ns/\mu A)\ \text{and}\ T_p = 57{,}8\,(ns) \qquad (A.6)$$

which leads to $1/a$ = 1 452 ns and $1/A$ = 537 ns. The coefficient $A$ can then be adjusted by calculating the correction and integration of the reference signal with $h(t)$ in order to obtain a flat result inside the sample. In Figure A.6, coefficient $1/A$ has been adjusted from 537 ns to 688 ns while coefficient $1/a$ is the same.

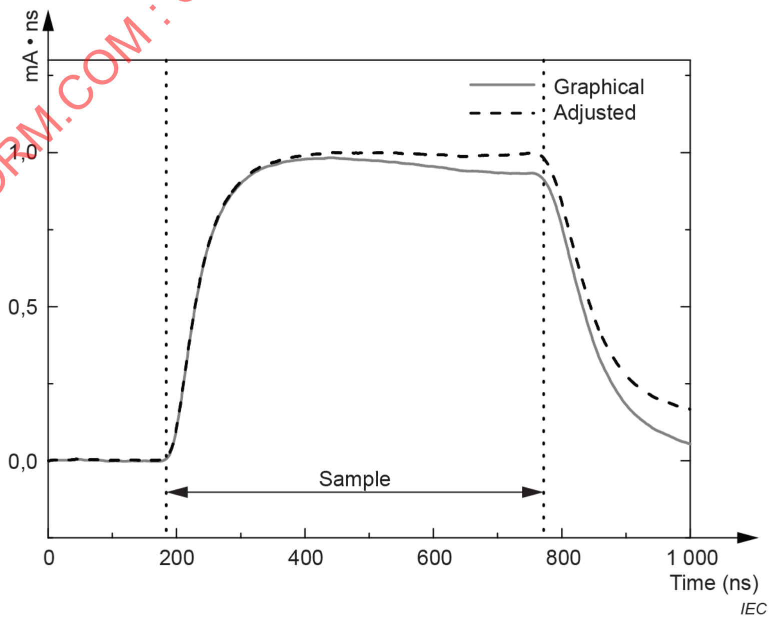



**Figure A.6 – Reference signal corrected with coefficients graphically obtained and adjusted**