

Theoretical and Experimental Studies of Off-the-Shelf V-dot Probes

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Abstract— The paper introduces the work undertaken to reliably use off-the-shelf differentiating voltage probes attached to coaxial transmission lines. The results obtained prove that indeed such probes are a valid and simple instrument for measuring nanosecond and subnanosecond voltage impulses. As a bonus, the research also highlighted an important challenging phenomenon that appears whenever an attempt is made to measure fast voltage impulses with a differentiating probe positioned too close to the closing switch of a pulse forming line generator.

Index Terms—Pulsed power systems, Voltage probes, Pulse Forming Lines

I. INTRODUCTION

THE measurement of fast transient high-voltages impulses in pulsed power experiments is well-known to be difficult and specialist conferences have been dedicated to it [1]. After being introduced in open literature in 1980 [2], V-dot probes have been successfully used in the next decades to measure fast transient kV and MV voltage signals generated by various impulse generators. In studying the published literature, with a few representative examples being [2-8], the general impression is that the design and implementation of a V-dot probe (sometimes termed D-dot or antenna) is something complicated. This feeling arises from the sometimes ingenious but certainly quite different probe geometries used by various pulsed power laboratories worldwide to solve their specific diagnostic requirements. This paper is however concentrating on the measurement of fast nanosecond and subnanosecond voltage impulses in *coaxial transmission lines*

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(TLs) and will demonstrate that use of 'standard' V-dot probes, simply made from off-the-shelf SMA- or N-type connectors and adaptors [9-11], represents a practical solution which potentially offers a simpler alternative to most of the design challenges associated with V-dot probes. The results of the present work are of particular interest for anyone in the domain aiming to obtain results straightforwardly, without losing precious time in developing a new V-dot probe design.

The paper also shows that, when V-dot probes are mounted onto a coaxial *pulse forming line* (PFL) generator the position must be carefully chosen. This is a recommendation valid for any probe design and not necessarily restricted to those probes made from off-the-shelf items.

II. STUDIES OF OFF-THE-SHELF N- AND SMA-TYPE V-DOT PROBES MOUNTED ONTO COAXIAL TRANSMISSION LINES

Numerical 3D electromagnetic analyses have been performed with CST Microwave Studio [12] for N-type female-female (Jack-to-Jack) adapters and for SMA-type panel connectors (Jack, flange mount 'candlesticks'), both used as *off-the-shelf* V-dot probes in coaxial TLs.

In Fig. 1 the N-type probe, shown mounted on a large outer diameter (110 mm) TL filled with polyethylene, has been investigated using a 6 GHz Gaussian voltage impulse injected through a CST port along the TL. Its integrated output signal is compared in Fig. 2 with the voltage signal provided by a CST voltage probe placed nearby (V in Fig. 2), with the two traces being indistinguishable! Additionally, (real) experiments were performed with the N-type probes either mounted on a bi-conical adaptor or attached to a high-voltage microwave cable using a metallic supporting element (Fig. 3). In both cases and using a vector network analyzer (VNA), it was proven that up to about 6 GHz their recorded characteristics were practically identical to the CST software predictions (Fig. 4).

Further CST-based studies also showed that by altering the N-type adaptor, either by cutting and removing a slice to allow placing the central pin in direct contact with the TL insulator or by filling the (initially hollow) pin with solder, are not improving the probe characteristics. The best remains to leave the off-the-shelf item as made by the manufacturer.

When used in a PFL generator, SMA-type V-dot probes were mounted onto a HV coaxial microwave cable type

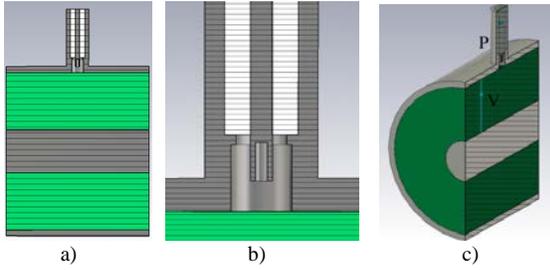


Fig. 1. a) CST model of an N-type adaptor used as a V-dot probe mounted onto a coaxial transmission line. b) Details of the probe. c) A CST voltage probe (V) is used to check the quality of signals generated by the differential V-dot probe (P).

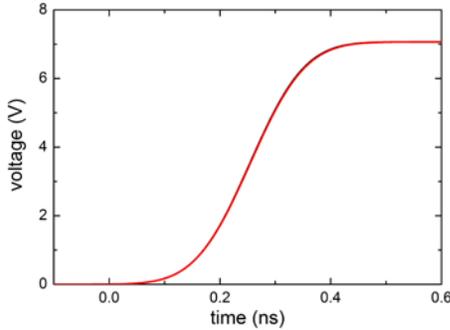


Fig. 2. The integrated output from an N-type V-dot probe (P in Fig. 1) is compared with the signal from a CST voltage probe (V in Fig. 1). The two signals are identical when a 6 GHz Gaussian signal is injected through a CST port along the transmission line.

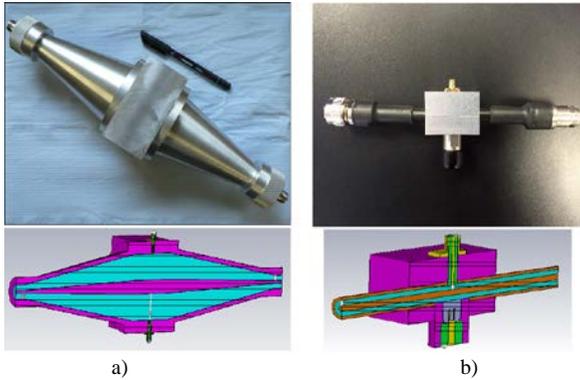


Fig. 3. Experiments with the N-type probe attached to: a) Bi-conical adaptor; b) High-voltage microwave cable using a metallic supporting element. For both experiments the corresponding CST model is shown below.

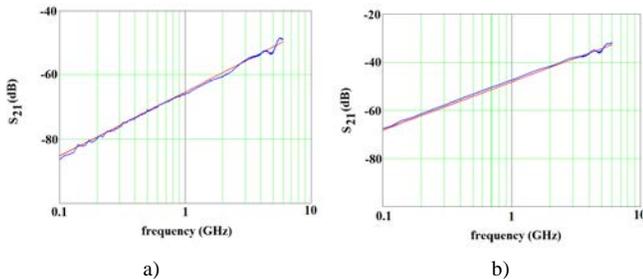


Fig. 4. The variation with frequency over a large bandwidth of the N-type probe S_{21} parameter obtained from experiments using a VNA is successfully compared with the corresponding CST predictions. a) and b) are in reference to Fig. 3

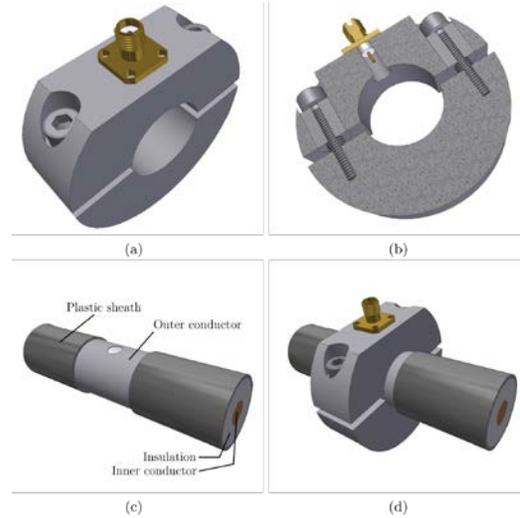


Fig. 5. SMA-type V-dot probe mounted onto a HV microwave cable (a) Drawing of the SMA-based V-dot probe. (b) Cut-away view: the tip of the bulkhead connector is the probe's electrode (c) HV microwave SA24272 cable with a hole in the outer conductor (d) V-dot sensor mounted onto cable. The drawings are taken from [9].

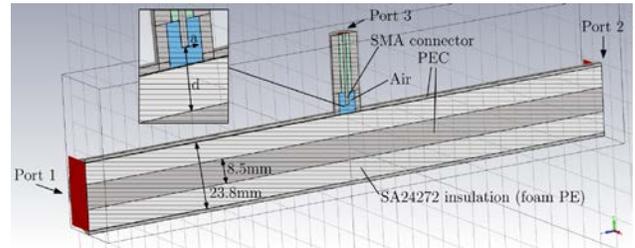


Fig. 6. CST model for the SMA-type V-dot probe shown in Fig. 5. Ports 1, 2 and 3 correspond to the input of the cable, the output of the cable and the output of the V-dot probe, respectively. Distances 'a' and 'd' are used in defining the mounting precision

SA24272 having a diameter of 23.8 mm (Fig. 5) [9]. CST-based numerical analysis (Fig. 6) and real experiments using a VNA proved that the experimental data matches the CST predictions over a large bandwidth: between 100 MHz up to well inside the GHz domain. As shown in Fig. 7, the difference between experimental data and theoretical predictions was found to be on average around 0.3 dB, which represents an error in measured amplitudes of about 3.5%.

III. CALIBRATION ISSUES

Can off-the-shelf probes attached to coaxial TLs be calibrated using only CST modelling? The answer to this question could be either negative or positive, as it depends on the mechanical mounting precision!

For example, in the case of small size transmission lines, the answer is rather negative. In such a case it is always a good practice to validate the initial CST calibration using a VNA. It is not a surprise that, to rely solely on CST calibration, the mounting of probes on a small-size transmission line is demanding. For example, for the SMA-type probe mounted on a 23.8 mm diameter transmission line, a $\pm 200 \mu\text{m}$ radial positioning error is predicted by CST to change the voltage amplitude by 15.5% and 19.4%, respectively! The results of a detailed CST study on the

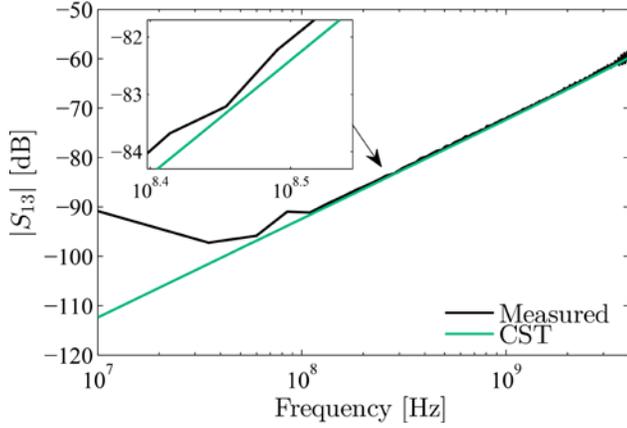


Fig. 7. Comparison between VNA measured and CST simulated S_{13} -parameters for the SMA-type V-dot sensor presented in Fig. 5.

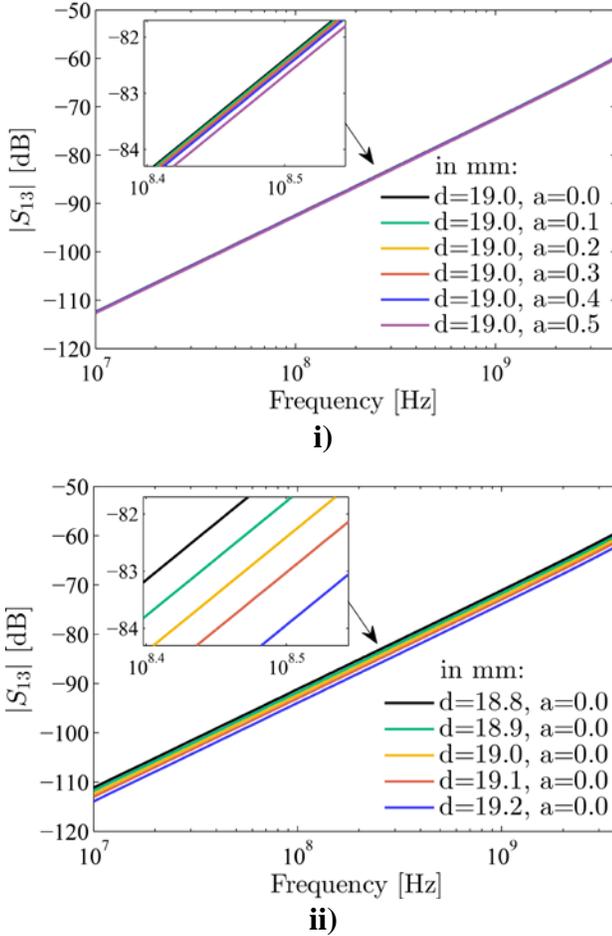


Fig. 8. Studies of the influence on the S-parameter of various characteristics related to mounting SMA-connectors on a HV cable
i) influence of the offset 'a' from its center position ii) influence of distance 'd' to HV electrode. The distances 'a' and 'd' are as in Fig. 6.

influence of mounting precision on the S-parameter are presented in Fig. 8. The influence of the distance from the tip of the SMA connector to the high voltage conductor (indicated by 'd' in Fig. 6) and the shift of the SMA connector axis from

the axis of the hole in the shield of the cable (indicated by 'a' in Fig. 6) are both considered.

However, for large diameter TLs the answer is rather positive. In such a case, the technique using a VNA is in practice expensive (both in time and money), because high bandwidth bi-conical adaptors require careful design and manufacturing. On the other hand, for a large diameter TL the use of CST results to calibrate the V-dot probe is realistically possible, as the required mounting precision is less demanding. For example, for N-type probes mounted on a 110 mm diameter TL, for the same $\pm 200 \mu\text{m}$ radial positioning error as above, the voltage amplitude is predicted by CST to only change between 1% and 5%, respectively!

A final note about calibration concerns the signal cables used to connect the V-dot sensors to the measuring instrument (e.g., the oscilloscope). When measuring high-frequency signals (i.e., in the GHz range), such cables can introduce a supplementary attenuation to the measured signals [9, 10]. It is important to always use as short as possible and extremely low-loss cables for such measurements. Alternatively, the measuring system can be calibrated for the loss of these cables (especially if they are very long), either by de-embedding their response in the measuring instrument, or by numerical reconstruction [9, 10, 13].

IV. A GENERAL ISSUE RELATED TO USING ANY TYPE OF V-DOT PROBES IN PFLS

Fig. 9 shows results obtained with an N-type V-dot probe mounted in a coaxial TL, at the output of a bipolar former [14] and about 100 mm from its spark-gap. The TL has an open end and the measured reflected signals seem to look much 'better' than the direct signals i.e., they are less distorted. As seen in Fig. 9, the distortions present in the direct signal are slightly changing from shot to shot. Fig. 10 shows similar results obtained with an improved version of the bipolar former. This time the V-dot probe is mounted further from the bipolar former spark-gap i.e., at a distance of about 350 mm. As a consequence, both the direct and the reflected signals have practically the same shape! The results above strongly suggest that *placing a V-dot probe too close to a spark-gap may generate distorted signals*. To understand this phenomenon better, a detailed CST study was undertaken using the arrangement presented in Fig. 11, with two probes (P) mounted onto a PFL and their signals compared with CST voltage probes (V). Firstly, in order to investigate if the phenomenon can be avoided using a better designed probe, three different V-dot probes were considered, as presented in Fig. 12: N-type, 'normal' and 'shielded'. The CST analysis demonstrated there is very little difference between the signals generated by these probes, as they are all affected when mounted too close to a spark-gap! It was also found that the phenomenon is enhanced if the PFL diameter is larger, but mostly if the spark-gap breakdown plasma channel is not situated along the central axis (see Fig. 13). As in a spark-gap the plasma channel position changes from shot to shot (Fig. 13), this may explain the fact that the amount of signal distortion also slightly differs from shot to shot (Fig. 14).

A further study showed the phenomenon being related to the spark-gap closure which generates non-TEM mode

attenuating or propagating (depending on the size of the TL) electromagnetic waves (besides a TEM mode wave) in the vicinity of the spark gap. These non-TEM mode waves may have electric-field components that are not purely perpendicular to the axis of the coaxial line (Fig. 15). As a consequence, the very fast time-of-change of the non-radial electric field components (Fig. 15a and 15b) do not allow an antenna to behave like a V-dot probe. For comparison, for a V-dot probe placed in a TL (i.e., no spark-gap present) the non-radial components play only a minor role (Fig. 15c). For a more detailed explanation let us consider the equivalent electric circuit of a V-dot probe [2], where the essential role is played by the capacitance between the pin (antenna) and the HV central electrode of the PFL. This capacitance is related to the radial electric field component generated inside the line. *If the time rate-of-change of the other electric field components begins to compete with the time-rate of change of the radial component, the antenna will not behave like a V-dot probe i.e., its output will not be proportional to the time-rate-of-change of the voltage impulse travelling along the line.* However, as the distance from the spark-gap at which the probe is mounted increases, this unwanted effect decreases because most of the non-TEM modes are attenuating modes. A study of the propagation of high-order modes in a transmission line is presented in Appendix 1.

The optimum position to mount a V-dot probe depends on the PFL diameter, with a small diameter being less demanding because a smaller diameter coaxial structure supports less higher-order propagating wave modes and the higher-order attenuating wave modes will attenuate over a shorter distance [15-17].

However, a simple general rule would be to place the probe as far from a spark-gap as allowed by the experimental arrangement.

V. CONCLUSIONS

The paper demonstrates, both theoretically and practically, that V-dot probes made from off-the-shelf N-type adaptors or SMA type connectors can be successfully used to measure fast transient voltage impulses in coaxial TLs. We are not advocating replacing the presently used V-dot probes with off-the-shelf components. We are only advising newcomers not to be intimidated by sophisticated literature designs and be encouraged to straightforwardly install and use off-the-shelf V-dot probes. As a bonus, the difficult task of calibrating such probes when used in large diameter transmission lines can in most cases rely solely on their CST modelling.

The paper also highlights an important perturbing factor inside coaxial PFLs that requires mounting any type of V-dot probes as far as possible from the PFL spark-gap, because of the unwanted influences of higher-order non-TEM wave modes.

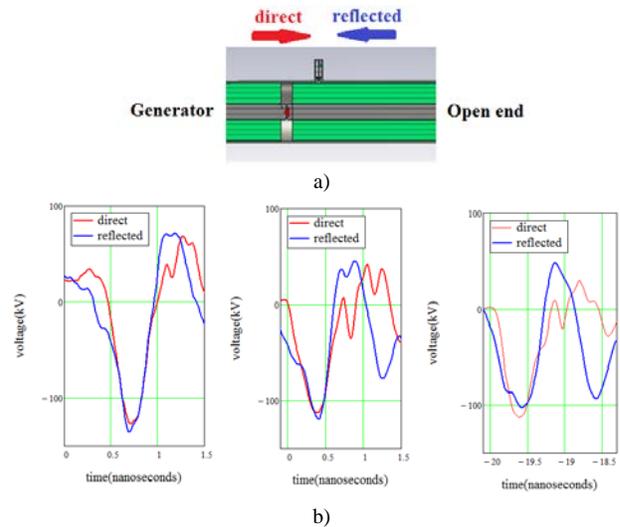


Fig. 9. a) N-type V-dot probe shown mounted onto an open ended coaxial transmission line at the output of a bipolar former about 100 mm from its spark-gap. b) Integrated voltage probe signals obtained from three different shots. For convenience, the reflected signal is shown as being generated at the same time as the direct signal.

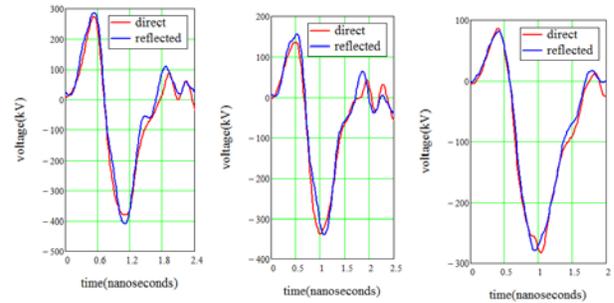


Fig. 10. Same type of results as in Fig.8, with the probe mounted about 350 mm from the spark-gap.

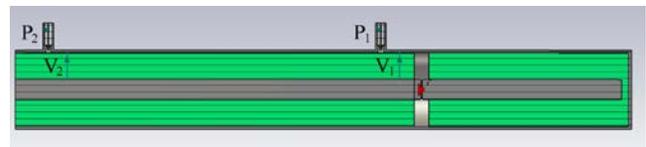


Fig. 11. CST model of a PFL with two N-type V-dot probes installed (P_1 and P_2). For each probe there is a CST voltage sensor (V_1 and V_2).

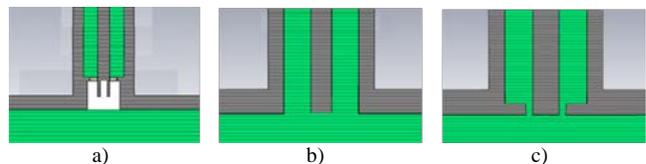


Fig. 12. Three possible V-dot designs: a) based on an N-type adaptor b) 'normal', with the central electrode (antenna) in contact with the transmission line dielectric and c) 'shielded'

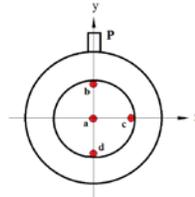


Fig. 13. Cross-section of a coaxial PFL showing four possible loci (a, b, c, d) for the spark-gap plasma channel in respect to the position of the V-dot probe P.

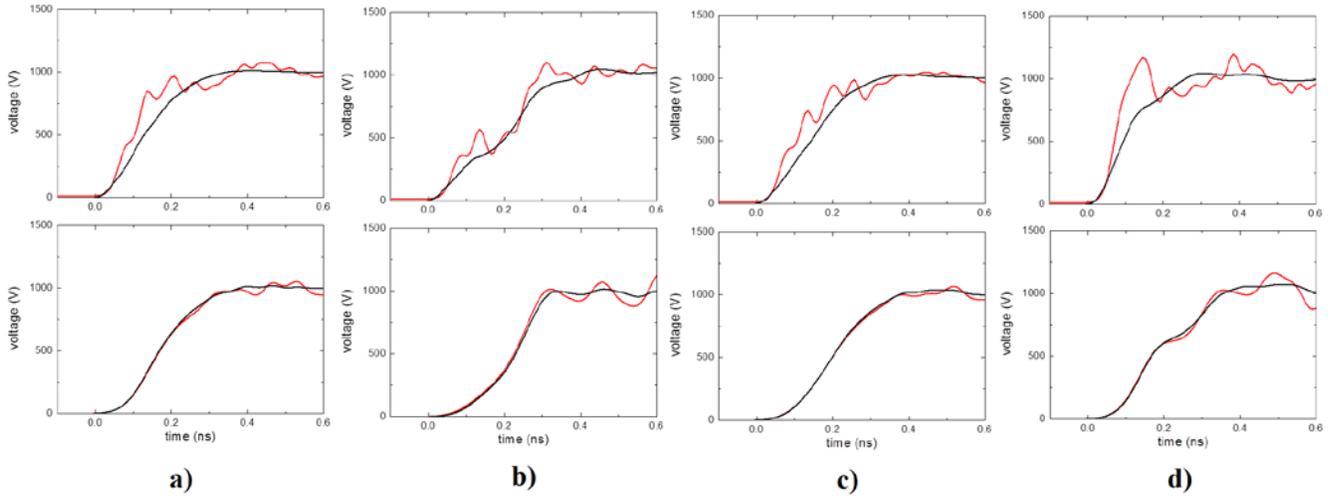


Fig. 14. The influence of the plasma channel position in a spark gap on the signal distortion of the two V-dot probes of Fig. 10. *Upper row*: integrated signals from the probe P₁ compared with the corresponding CST voltage probe V₁. *Lower row*: same for the pair P₂ and V₂. *Columns a, b, c and d* correspond to the positions of the spark-gap plasma channel, as in Fig. 13.

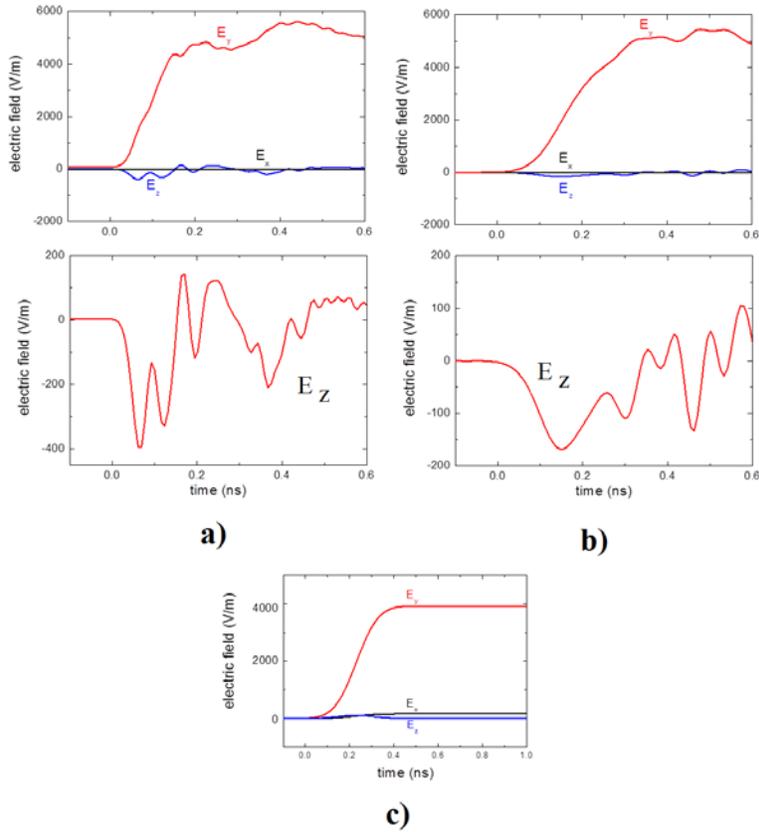


Fig. 15. Time dependence of the electric field vector components in a PFL a) for probe P₁ and b) for probe P₂. The probes are positioned as in Fig.11. c) the time dependence of the electric field vector components for a V-dot probe placed in a TL as in Fig. 1. Electric field Ox and Oy axes are as in Fig.13, with the Oz along the transmission line axis.

APPENDIX 1

As suggested by CST simulations, high-order modes are probably excited due to the random breakdown of spark-gap switch, forming off-axis (asymmetric) plasma channels. In addition, breakdown processes leading up to and during the early stages of the spark-gap switching can have such a high-frequency nature, that higher-order modes can be excited (even though most will be attenuating modes).

In what follows, a brief analysis of the TM and TE propagating modes in a coaxial waveguide is provided.

The field-component expressions in cylindrical coordinates for the TM modes are [1]:

$$\begin{aligned} E_r &= -j\beta T U_0 \left[N_n(Ta) J_n'(Tr) - J_n(Ta) N_n'(Tr) \right] \cos(n\phi) e^{-j\beta z}, \\ E_\phi &= -j \frac{\beta n}{r} U_0 \left[N_n(Ta) J_n(Tr) - J_n(Ta) N_n(Tr) \right] \sin(n\phi) e^{-j\beta z}, \\ E_z &= T^2 U_0 \left[N_n(Ta) J_n(Tr) - J_n(Ta) N_n(Tr) \right] \cos(n\phi) e^{-j\beta z}, \\ H_r &= -j \frac{\omega \varepsilon n}{r} U_0 \left[N_n(Ta) J_n(Tr) - J_n(Ta) N_n(Tr) \right] \sin(n\phi) e^{-j\beta z}, \\ H_\phi &= -j \omega \varepsilon T U_0 \left[N_n(Ta) J_n'(Tr) - J_n(Ta) N_n'(Tr) \right] \cos(n\phi) e^{-j\beta z}, \\ H_z &= 0. \end{aligned} \quad (1)$$

where J_n and N_n are the n -th order first kind and second kind Bessel functions and J_n' and N_n' are their corresponding differentials, respectively; U_0 is the normalized field amplitude for the TM modes; T is the transverse wave-number and β is the longitudinal wave-number satisfying the relation $k^2 = T^2 + \beta^2$, where $k = 2\pi f \sqrt{\mu_r \varepsilon_r} / c$.

The dispersion equation for the TM mode in a coaxial waveguide is:

$$J_n(Tb) N_n(Ta) - J_n(Ta) N_n(Tb) = 0. \quad (2)$$

where a and b are the outer and inner radii of the coaxial waveguide, respectively.

The field-component expressions (in cylindrical coordinates) for the TE modes are [1]:

$$\begin{aligned} E_r &= \frac{j\omega \mu n}{r} V_0 \left[N_n'(Ta) J_n(Tr) - J_n'(Ta) N_n(Tr) \right] \sin(n\phi) e^{-j\beta z}, \\ E_\phi &= -j\omega \mu T V_0 \left[N_n'(Ta) J_n'(Tr) - J_n'(Ta) N_n'(Tr) \right] \cos(n\phi) e^{-j\beta z}, \\ E_z &= 0, \\ H_r &= -j\beta T V_0 \left[N_n'(Ta) J_n'(Tr) - J_n'(Ta) N_n'(Tr) \right] \cos(n\phi) e^{-j\beta z}, \\ H_\phi &= \frac{j\beta n}{r} V_0 \left[N_n'(Ta) J_n(Tr) - J_n'(Ta) N_n(Tr) \right] \sin(n\phi) e^{-j\beta z}, \\ H_z &= T^2 V_0 \left[N_n'(Ta) J_n(Tr) - J_n'(Ta) N_n(Tr) \right] \cos(n\phi) e^{-j\beta z}, \end{aligned} \quad (3)$$

where V_0 is the normalized field amplitude for the TE modes.

The corresponding dispersion equation for the TE mode in a coaxial line is given by:

$$J_n'(Tb) N_n'(Ta) - J_n'(Ta) N_n'(Tb) = 0. \quad (4)$$

T can be obtained from the dispersion equations, but we decided to use CST to obtain the cutoff frequency f_c , from which T can be obtained from:

$$T = \frac{2\pi f_c}{c} \sqrt{\mu_r \varepsilon_r} \quad (5)$$

while the corresponding group velocity v_g is given by:

$$v_g = \frac{c}{\sqrt{\mu_r \varepsilon_r}} \sqrt{1 - \frac{T^2}{k^2}} \quad (6a)$$

which can be re-written as:

$$v_g = \frac{c}{\sqrt{\mu_r \varepsilon_r}} \sqrt{1 - \frac{\lambda_c^2}{\lambda^2}} \quad (6b)$$

where λ_c is the cutoff wavelength ($\lambda_c f_c = c / \sqrt{\varepsilon_r}$).

As a first example let us consider $a = 20$ mm, $b = 6$ mm, and $\varepsilon_r = 2.1$ for which the cut-off frequencies of the TE₁₁ and the TE₂₁ mode are 2.6 GHz and 4.89 GHz, respectively. We note that the cut-off frequencies of the TM₀₁ mode and TM₁₁ mode are 7.26 GHz and 7.75 GHz respectively. These frequencies are much higher than those for the TE modes and therefore are more difficult to be excited. As $k^2 = T^2 + \beta^2$, for an attenuating wave with the frequency less than the cutoff frequency β will be an imaginary number and for the present case $\beta = -21.6i$. Using the field-component Eqs (1) and (3) it is obvious that the term $e^{-j\beta z}$ is attenuated as the wave travels along the coordinate z , or in other words the TE₁₁ mode will have an e -fold decay ($1/e$) after about 5 cm.

It is possible that the TEM, TE₁₁ and TE₂₁ mode are all excited at the same time by the spark-gap switch. Let us assume the frequencies of the excited TE₁₁ mode and TE₂₁ mode to be 5 GHz, and 10 GHz, respectively. In such conditions, it can be calculated that the group velocities of the TEM mode, TE₁₁ mode and TE₂₁ mode are 20.7 cm/ns, 17.68 cm/ns, and 18.06 cm/ns, respectively. If the pulse rise time is t_r , in order to avoid the higher-order mode disturbing the rise edge, the length L of transmission line between the spark gap and the V-dot probe should satisfy the condition:

$$\frac{L}{v_{TE_{21}}} - \frac{L}{v_{TEM}} > t_r \quad (7)$$

In the present case for $t_r = 0.2$ ns, $L > 28$ cm. For the TM₀₁ mode and TM₁₁ mode with frequencies of 10 GHz, the group velocities are 14.2 cm/ns and 13.1 cm/ns, respectively and therefore $L > 9$ cm. From this point of view, *for the same frequency*, the mode with lower cutoff frequency will need longer distance to avoid the disturbance, so the higher-order mode with a higher cutoff frequency can be neglected.

As a second example let us consider $a = 60$ mm, $b = 18$ mm, $\varepsilon_r = 2.1$, for which the cutoff frequencies of the TE₁₁ mode and TE₂₁ mode are 0.868 GHz and 1.63 GHz, respectively. For

the same frequencies of the TE₁₁ mode and TE₂₁ mode as before (i.e., 5 GHz and 10 GHz), the group velocities of the TEM mode, TE₁₁ mode and TE₂₁ mode are 20.7 cm/ns, 20.39 cm/ns, and 20.40 cm/ns, respectively. In this case for $t_r = 0.2$ ns, $L > 2.8$ m. We note that the group velocities are dependent on both the cut-off frequency *and* the frequency of electromagnetic wave. On the other hand, the cut-off frequency is determined by the dimensions of the coaxial waveguide. Because the TE₁₁ and TE₂₁ mode are the modes with the lowest cutoff frequencies, for other modes with higher cutoff frequency less distance will be required to avoid any disturbance.

As a conclusion, to avoid a higher mode disturbance, the distance a V-dot probe can be placed from a spark gap and measure the correct rise time increases with the radius of the waveguide and with the frequency. Finally, the larger the frequency difference between the cutoff frequency and the high frequency signal, the longer this distance will be.

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