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Features of Recording the Time Profile of Single Picosecond Pulses in the Real-Time Mode

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Abstract—A technique for measuring the time profile of a beam-current pulse of runaway electrons that are generated in atmospheric-pressure air is described. The analysis of changes in the pulse shape depending on the bandwidth of the registration path with a temporal resolution of up to 20 ps was performed. It was shown that the electron beam detected behind small-diameter diaphragms has a complicated structure, which depends on the parameters of the gas diode. The issues related to the interpretation of subnanosecond pulses that are picked off capacitive voltage sensors are discussed.

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INTRODUCTION

The development of oscilloscopic methods in investigations of fast processes in gas discharges is determined by the advent of modern digital oscilloscopes operating in the real-time mode with a bandwidth of ⩾30 GHz and a sampling frequency of >80 × 10^9 points/s [1–3]. These measuring instruments are primarily aimed at the solution of problems in microelectronics, computer engineering, digital communication channels, etc., and substantially facilitate the work of engineers when developing and checking the correspondence of signals of high-speed serial data transfer to standards.

At the same time, the use of real-time digital oscilloscopes with a wide passband Δf makes it possible to register the time profile and amplitude values of single electric signals, which are formed by current and voltage sensors in studies of prebreakdown phenomena in the gas-discharge physics [4–9]. At the frequency band of input analog paths of oscilloscopes $\Delta f \sim 30$ GHz, it becomes possible to register features of the time profile of signals with a temporal resolution of up to 10 ps.

The process of generating a runaway-electron (RE) beam in gases with an increased pressure, when a gas diode is excited with high-voltage nanosecond pulses with subnanosecond fronts, is one of such fast processes. In this case, questions arise that are related not only to the correct determination of the RE-beam current shape but also to the determination of the voltage across the discharge gap and their mutual positions on the time axis with the picosecond accuracy.

The first problem in such measurements is associated with both the impossibility of placing a voltage sensor directly in the discharge gap and the necessity of conducting indirect measurements on the basis of readings of the sensors that are installed in a feeding coaxial line at a certain distance from the discharge gap. The limitations that arise in such a measurement will be discussed below in Section 3.

Another factor that appears during registering of subnanosecond pulses is the operation of the registration path of a digital oscilloscope operating in the real-time mode near the upper edge f_h of the passband. The mathematical apparatus for digital signal processing (DSP) that is used in modern oscilloscopes for compensating nonuniformities in the amplitude–frequency characteristics of channels properly operates in the case of a pulse–periodic mode. When operating in the single-pulse mode, DSP filters may introduce additional distortions into a registered signal (before/after) in the form of surges, whose characteristic times are comparable to the rise time t_r of the oscilloscope transient characteristic. In connection with this, the question on the reliability of the obtained data in measurements of the time profiles of single pulses near f_h arises, and it is of interest to compare the shapes of signals of picosecond durations that are recorded using different oscilloscopes with close values of Δf.

The objective of this study was to reveal the specific features of measuring the time profile of single pulses, whose duration is comparable to the temporal resolution of modern real-time oscilloscopes, and determine the range of reliable measurements of RE-beam current pulses and the gas-diode voltage that corresponds to them.

1. EXPERIMENTAL SETUP

The experimental setup included a driving generator of single high-voltage pulses of negative polarity, which was loaded into a gas-filled diode. When the discharge gap is broken down, an RE beam is generated [4–7], which forms a voltage pulse in the collector unit mounted behind the anode foil of the diode.

A SLEP-150M generator that was specially developed for forming an RE beam was used in this study as the driving source of high-voltage pulses [9]. A peaking spark gap of the generator is broken down at a voltage of the forming line of ~140 kV; in this case, a pulse with a duration of ~1 ns and a rise time of ~300 ps appears in the oil-filled coaxial transmission line with diameters of the outer and inner electrodes of 68 and 6 mm, respectively.

The generator is loaded into a gas diode that is filled with atmospheric-pressure air. A stainless-steel tube with a 6-mm diameter and 0.1-mm-thick wall, which is connected to the central electrode of the output line and separated from the transmission line by a feedthrough insulator, serves as the cathode. The anode, which is positioned at a distance of 12 mm from the cathode, is a 10-μm-thick aluminum foil.

The RE-beam current was recorded using coaxial collector units (Fig. 1) with a 20- (collector *A*) and 3-mm-diameter (collector *B*) receiving parts. Collimator *4* was mounted in front of collector *B* at a distance of 5 mm from it. The diaphragm *5* of collimator was 5 mm thick, and the hole in it was 1 mm in diameter. The dimensions of the diaphragm were selected such that the entire electron beam that passed through the collimator was incident on the receiving end face of collector *2*. A real-time oscilloscope was connected through a coaxial cable to the output connectors of the collector units.

Registering fast processes imposes certain requirements on the used sensors: registering REs requires the use of a measuring path with a picosecond time resolution. The collector must have a small-size receiving part and register signals from small-area segments of the anode foil. An increase in the area of the receiving part of the collector leads to an increased duration of a registered pulse; in this case, information on the time profile of the RE-beam current, which emerges through different anode-foil areas, is lost.

Table

No.	Oscilloscope type	f_h, GHz	Sampling frequency, 10^9 points/s	t_r, ps
1	Tektronix DPO70604	6	25	65
2	Tektronix MSO71254	12.5	50	32
3	Tektronix TDS6154C	15	40	28
4	Tektronix MSO72004C	20	100	18
5	Tektronix DSA72504D	25	100	16
6	LeCroy WaveMaster 830Zi	30	80	15.5

To obtain the pulse characteristics of the collectors, a numerical experiment was performed (using the fully electromagnetic KARAT PIC code [10]), in which the collector was excited by an incident short-duration electron bunch (several picoseconds). The FWHM durations of the pulse characteristics of collectors *A* and *B* were about 70 and 22 ps, respectively. Measurements of the amplitude– and phase–frequency characteristics of the path, which included the collector, cables, and connectors, were also performed using an Agilent Technologies E8363B circuit analyzer in a range of 0.01–40 GHz [4, 5].

2. RECORDING OF CURRENT PULSES

Signals from collectors were recorded using real-time oscilloscopes with the upper edge of the passband f_h and the certified rise time of the transient response t_r (see the table). It should be noted that this class of oscilloscopes contains a mathematical package that allows automatic statistical processing of the measured

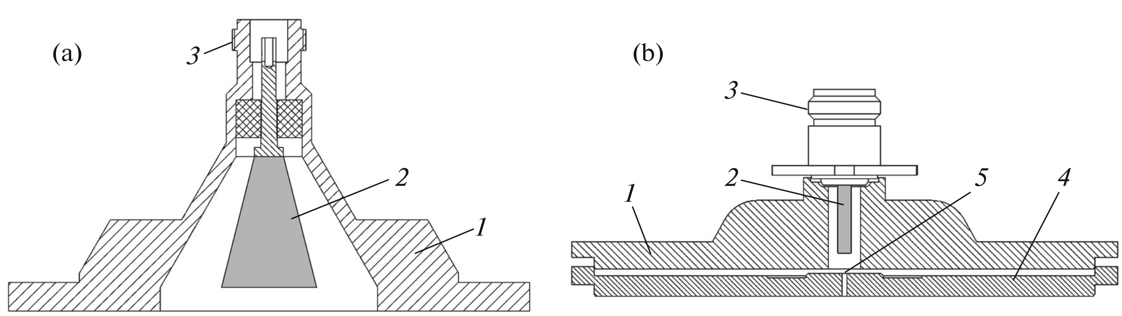

Fig. 1. Designs of collector units *A* (a) and *B* (b): (1) case; (*2*) receiving part; (*3*) output connector; (*4*) collimator; and (*5*) diaphragm.

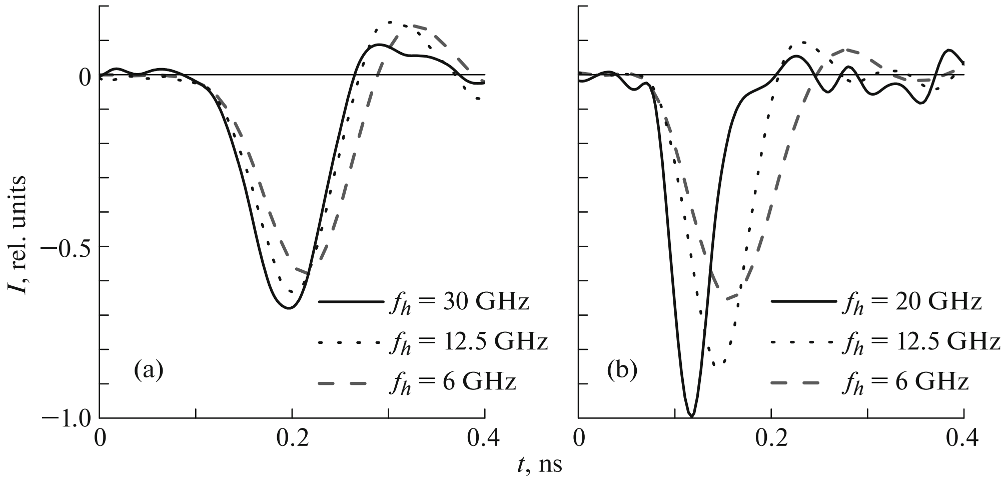

Fig. 2. Beam-current profiles recorded with oscilloscopes no. 1 (f_h = 6 GHz), no. 2 (f_h = 12.5 GHz), no. 4 (f_h = 20 GHz), and no. 6 (f_h = 30 GHz) for collectors (a) *A* and (b) *B*.

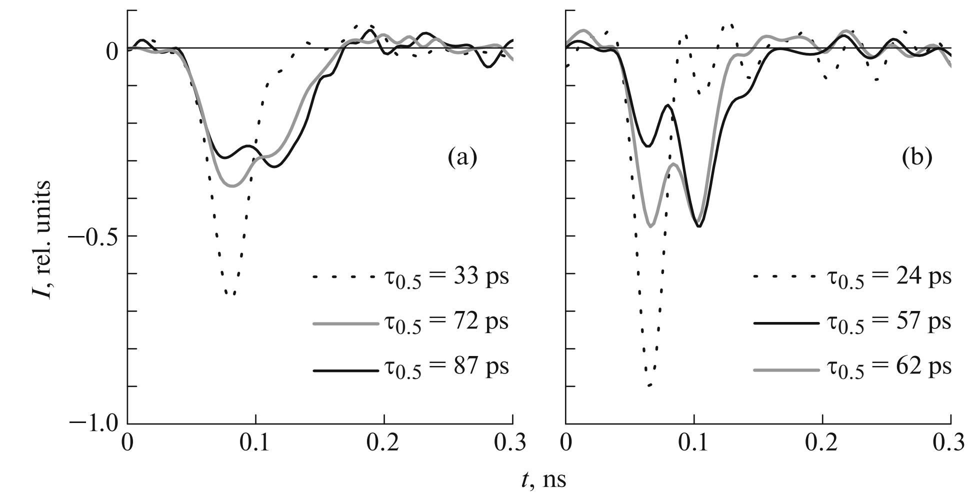

Fig. 3. Pulses of the RE-beam current of collector *B* that were recorded with oscilloscopes (a) no. 5 (f_h = 25 GHz) and (b) no. 6 (f_h = 30 GHz).

quantities: the minimum, maximum, and averaged values, standard deviation, and distribution.

2.1. Registration of Ultrashort Pulses of the RE Beam Current

The results of measuring the time profile of RE-beam current pulses as a function of Δf of the registration path are presented in Fig. 2. The curves are normalized so that the areas under them are identical. This approach makes it possible to compare the time profiles of the current at different f_h of the used oscilloscopes and an identical total charge transferred by the RE beam.

When Δf of the registration path is small (collector *A* is used), the use of oscilloscopes with t_r < 60 ps is a surplus procedure: the FWHM duration of a registered pulse is at least 85 ps. At the same time, when a registration path with a short t_r is used, oscilloscopes operate near f_h and actually record their own pulse characteristic as the response to a short action: the FWHM pulse durations for oscilloscopes nos. 1, 2, and 4 are 90, 67, and 45 ps, respectively (Fig. 2b).

The fine time structure of an RE-beam current pulse that passes through the anode foil and the 1-mm-diameter diaphragm manifested itself when oscilloscopes with Δf > 25 GHz were used (Fig. 3). Measurements using collector *B* and oscilloscopes nos. 5 and 6 showed that the time profile of RE-beam current pulses behind the small-diameter diaphragm may differ from pulse to pulse under constant experimental conditions.

In these measurements, one part of pulses had the shape of a single peak with an ultimately short FWHM duration $\tau_{0.5} = 24–25$ ps for the used registration path. The second group of pulses had a single-peak structure and $\tau_{0.5} \approx 35–45$ ps. The third group of observed pulses consisted of two peaks whose amplitude could be identical or differed by several times. The time interval between peaks was determined by the sampling frequency of the oscilloscopes (one or two actual points in a sample fell within the minimum) and had a value of ~38 ps. A decrease in the amplitude between peaks is more pronounced for oscilloscope no. 6 (Fig. 3b).

When the 10-μm-thick anode aluminum foil was replaced by a 60- or 110-μm-thick aluminum foil, the two-peak structure of RE-beam current pulses was also registered. Because the two-peak structure is displayed at different foil thicknesses, it can be presumed that the electron energy in both peaks of an RE pulse differs insignificantly; hence, the voltage across the gap during the RE generation also does not appreciably change under such conditions.

The results of experiments using oscilloscopes nos. 5 and 6 showed that, when measuring the RE-beam current using a collector unit with the small-diameter receiving part, the passband of the registration path and f_h of the oscilloscope (30 GHz) are insufficient for revealing all the features of the time profile of an RE beam. The processes that lead to the single-peak RE generation mode with a FWHM pulse duration that is comparable to the pulse characteristic of the registration path (~25 ps) are evidently faster and require the application of measuring instruments with large f_h values.

2.2. Registration of Subnanosecond RE-Beam Current Pulses

Measurements of the electron-beam current behind large-diameter diaphragms show that at amplitudes of the RE-beam current of ⩾10 A, its duration is ~100 ps. However, the question on the exact pulse duration of the total electron current from the entire surface of the anode foil remains open because of several factors. First, as the collector diameter increases, its time resolution deteriorates, thus leading to the pulse elongation. Second, because of the large dimensions of the accelerating gap in the gas diode, the time profile of the RE-beam current is blurred. We tried to evaluate the real duration of a current pulse of REs that are incident on 20-mm-diameter receiving part *2* (Fig. 1a) of collector *A*.

To evaluate the pulse characteristic of collector *A*, the inverse problem using the regularization methods [11] was solved: a Gaussian-shaped action with a FWHM duration of 10 ps was used as the input action on the collector unit as a linear circuit, and the response was an output voltage that resulted from the numerical simulation of the collector. The obtained pulse characteristic was used to reconstruct the shape of the beam current acting on the collector on the basis of the experimentally obtained oscillograms at the collector output. The FWHM duration of the pulse characteristic of collector *A* is 70 ps; at a duration of the recorded pulses in a range of 85–110 ps (Fig. 2a), the duration of beam-current pulses then may be 70–90 ps, respectively.

3. CALCULATION OF VOLTAGE PULSES IN A COAXIAL LINE

A direct measurement of the voltage across the gas-discharge gap is impeded by its small dimensions, which are much smaller than the transverse size of the feeding coaxial line in typical experiments. Therefore, experimentalists limit themselves to an indirect measurement, in which signals are picked off several capacitive dividers that are positioned in the line at a certain distance from the discharge gap, and the voltage shape across the gap is reconstructed by the reflectometry method (see, e.g., [6–8]). It is obvious that such a method is applicable at a pulse duration in the line that considerably exceeds the electromagnetic-wave travel time across the line, i.e., when the excitation of higher modes in the line is excluded.

To determine the typical pulse durations at which this limitation manifests itself under the conditions of a particular experiment, a numerical experiment using the axially symmetric version of the KARAT code [10] was performed.

The line of the SLEP-150M facility, which terminated in an open gap, was simulated without taking possible discharge phenomena in this gap into account. The geometry of the problem is shown in Fig. 4. A 500-mm-long section of the coaxial line with 68-mm-diameter outer electrode *1* and 6-mm-diameter inner electrode *2*, which is filled with ideal dielectric *3* with a relative permittivity of 2.3, terminates in conical air cavity *4* and anode *5*. The distance between electrode *2* (cathode) and anode *5* is 10 mm. The distances *r* from the axis of the coaxial line and *z* from the anode to the measured points *p*1–*p*4 are as follows:

Point number	*p*1	*p*2	*p*3	*p*4
r, mm	32	3	1	1
z, mm	20	20	10	0

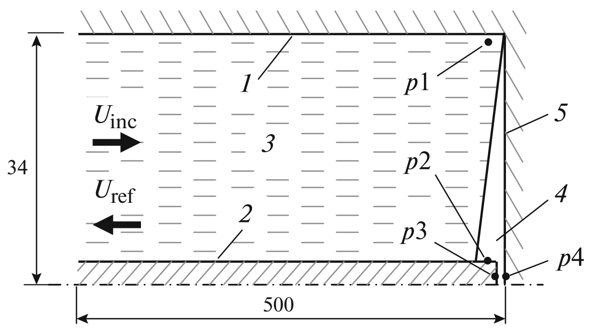

Fig. 4. Geometry of the calculation model of the coaxial transmission line and the gas-filled diode of the SLEP-150M generator: (*1*) outer electrode of the coaxial line; (*2*) inner electrode of the coaxial line (cathode); (*3*) transformer oil; (*4*) diode interelectrode gap; (*5*) anode; and (*p*1–*p*4) test points.

A trapezoidal pulse of a TEM wave with the voltage $U_{inc}(t)$ and durations of the leading and trailing edges τ_l and τ_{tr}, which are equal to $\tau_l = \tau_{tr} = 0.5\tau_{0.5}$, was fed to the line input. The waveforms of the reflected voltage wave $U_{ref}(t)$ at the line input, the radial electric field $E_r(t)$ at point *p*1 (in the experiment, this is the closest point to the discharge gap at which a capacitive divider can still be placed), the voltage $U_{12}(t)$ between point *p*2 and *p*1, and the voltage in the gap $U_{34}(t)$ (between points *p*4 and *p*3) were recorded. For convenience of the further description, let us introduce the concept of the spatial extension of a pulse in the medium $v\tau_{0.5}$, where v is the velocity of an electromagnetic wave in the dielectric material, and $\tau_{0.5}$ is the FWHM duration of the voltage pulse.

For nanosecond pulses ($v\tau_{0.5} \geqslant r_2 - r_1$), the time profile of the reflected wave reproduces the shape of the incident wave with insignificant distortions (Fig. 5a); in this case, $U_{12}(t) = U_{34}(t) = 2U_{inc}(t)$, and the time profile of the field strength $E_r(t)$ coincides with $U_{12}(t)$ and $U_{34}(t)$ (Fig. 6a).

In the subnanosecond range of pulse durations at $\tau_{0.5}$ > 500 ps ($v\tau_{0.5} \geqslant 4(r_2 - r_1)$), the shape of the reflected wave differs from U_{inc}, but the rise time (~300 ps) and $\tau_{0.5}$ remain virtually the same, and surges do not exceed 10% of the maximum amplitude (Fig. 5b). Signals $U_{inc}(t)$ and $U_{ref}(t)$ allow one to evaluate the time dependences of the quantities $E_r(t)$, $U_{12}(t)$, and $U_{34}(t)$, which virtually reproduce the shape of the signal calculated according to the time-reflectometry method [8] (Fig. 6b).

For shorter pulses when $\tau_{0.5} < 200$ ps ($v\tau_{0.5} \leqslant r_2 - r_1$), more significant distortions in the time profile are observed. A reflected-wave pulse becomes alternating, additional time lobes appear, and the total pulse duration at a level of 0.1 increases to 0.8 ns at a duration of the acting pulse of $\tau_{0.5} = 0.1$ ns (Fig. 5c). The shapes of the pulses $E_r(t)$ and $U_{12}(t)$ considerably differ from the shape of the calculated pulse $U_{inc}(t) + U_{ref}(t - \Delta t)$ (Δt is the time delay between the appearance of $U_{inc}(t)$ and $U_{ref}(t)$ in the input cross section of the feeding coaxial line) and also differ from each other (Fig. 6c). Hence, pulses with rise times that are shorter than 300 ps, which are registered with the divider at point *p*1 (they are proportional to the field $E_r(t)$) or with capacitive dividers that are installed in the transmission line of the generator, do not correspond to both the voltage $U_{12}(t)$ and the voltage across the discharge gap $U_{34}(t)$.

Thus, the aggregate of the obtained data allows us to suggest that the time range within which voltage sensors on coupled lines (capacitive dividers) are used is more than several hundreds of picoseconds and requires careful interpretation within a shorter time interval.

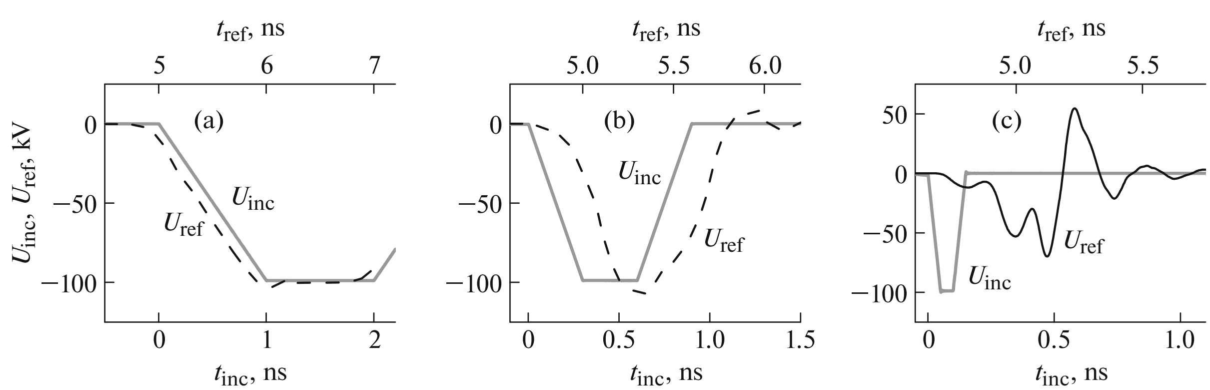

Fig. 5. Time profiles of the incident and reflected waves in the input cross section of the line at $\tau_{0.5}$ = 2 (a), 0.6 (b), and 0.1 ns (c).

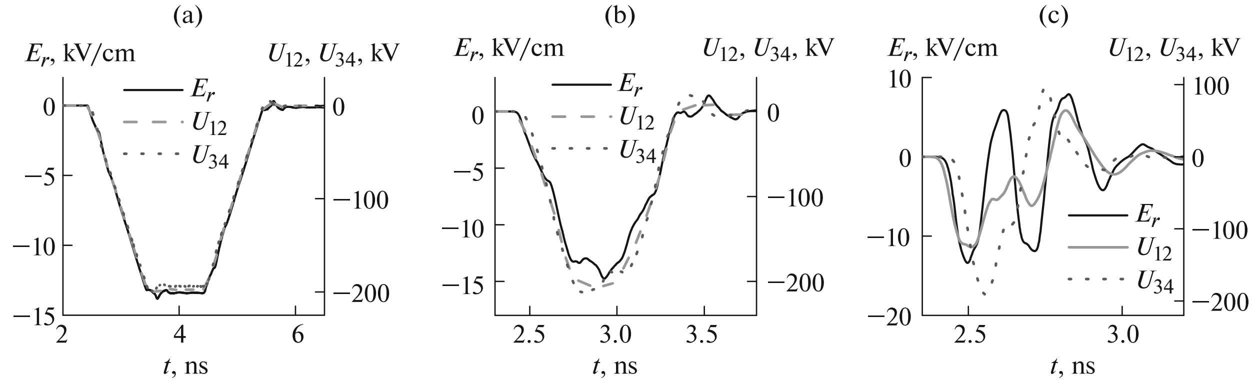

Fig. 6. Time profiles of the voltages $U_{12}(t)$, $U_{34}(t)$ and the field strength $E_r(t)$ at $\tau_{0.5} = 2$ (a), 0.6 (b), and 0.1 ns (c).

CONCLUSIONS

The performed investigations showed the possibility of registering RE-beam current pulses using modern real-time digital oscilloscopes in the single-pulse mode. At a passband of ~30 GHz and a sampling frequency of more than ~80 points/ns, RE-beam current pulses with an FWHM duration of ~20 ps, which passed through 1-mm-diameter and smaller holes in the anode, were registered.

The numerical simulation of the high-voltage coaxial line showed that the time profile of the voltage across the discharge gap can be determined from measured pulses of incident and reflected waves, when a spatial pulse length in the line-filling medium exceeds the fourfold width of the gap between the inner and outer coaxial electrodes (for the considered geometry of the feeding coaxial line, the FWHM voltage-pulse duration must be at least 600 ps with a rise time of ~300 ps or more). There is no unambiguous correspondence of the voltage in the line to the voltage across the discharge gap at shorter pulses.

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REFERENCES

1. http://www.agilent.com
2. http://www.lecroy.com
3. http://www.tektronix.com
4. Baksht, E.Kh., Balzovskii, E.V., Klimov, A.I., Kurkan, I.K., Lomaev, M.I., Rybka, D.V., and Tarasenko, V.F., *Instrum. Exp. Tech.,* 2007, vol. 50, no. 6, p. 811.
5. Tarasenko, V.F., Rybka, D.V., Burachenko, A.G., Lomaev, M.I., and Balzovsky, E.V., *Rev. Sci. Instrum.,* 2012, vol. 83, p. 086106. DOI: doi 10.1063/1.4746378
6. Tarasenko, V.F., *Plasma Phys. Rep.,* 2011, vol. 37, no. 5, p. 409.
7. Shao, T., Tarasenko, V.F., Zhang, Ch., Burachenko, A.G., Rybka, D.V., Kostyrya, I.D., Lomaev, M.I., Baksht, E.Kh., and Yan, P., *Rev. Sci. Instrum.,* 2013, vol. 84, p. 053506. DOI: doi 10.1063/1.4807154
8. Sharypov, K.A., Shpak, V.G., Shunailov, S.A., Ul'masculov, M.R., and Yalandin, M.I., *Rev. Sci. Instrum.,* 2013, vol. 84, p. 055110. DOI : doi 10.1063/1.4804355
9. Kostyrya, I.D., Baksht, E.Kh., and Tarasenko, V.F., *Instrum. Exp. Tech.,* 2010, vol. 53, no. 4, p. 545.
10. Tarakanov, V.P., *User's Manual for Code KARAT*, Springfield, VA: Berkley, 1992.
11. Tikhonov, A.N. and Arsenin, V.Y., *Solutions of Ill-posed Problems,* Washington: Winston, 1977.

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