Current Probes for Picosecond Electron Beams[1]

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Abstract – The results of calculations, developments and tests of collector-type current probes for electron beams with FWHM up to 45–50 ps are presented in the report. Such diagnostic devices are adequate to novel, digital real time oscilloscopes according to the transient response attaining 20–30 ps. The bandwidth limitations of the probes and reasons of pulse form distortion are analyzed in real experiments. Probes allow to registry with absolute timing the currents of picosecond beams differs in amplitude to three orders, and also perform time-of-flight measurements of the energy of relativistic electron beam possessing a picosecond rise time of current pulse.

1. Introduction

The effectiveness of investigations in the field of picosecond pulsed power electronics, alongside with considerable progress in the field of creating of high-voltage generators [1, 2] is, in all respects, determined by progress of metrology. In this aspect it should be noted a digital real time oscilloscopes whose transient responses reach 20–30 ps with the sampling interval of 20–25 ps. It is obvious that creation of probes for e-beams with duration ~ of 100 ps and less is of great importance for obtaining a correct experimental data.

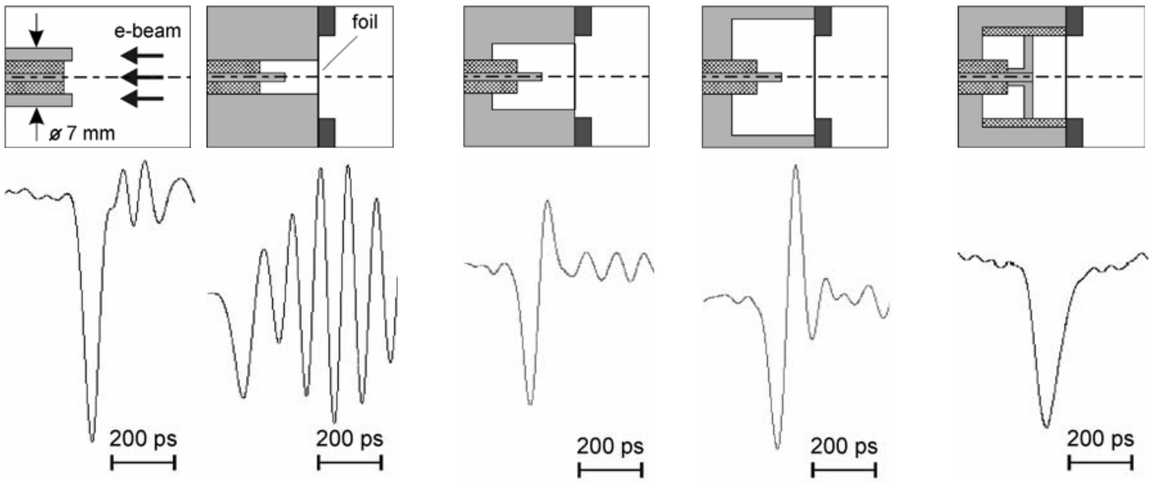
In the time range of beam currents above ten and more nanoseconds it is usually possible to use the Rogowski loops or registration circuits, where collector (anode) is connected to “the earth” through a voltage divider (resistive or capacitive) and the signal is recorded from the low-voltage arm of the divider. With that, the problem of amplitude attenuation could be solved. In the picosecond time range the dividers with lumped elements are inapplicable because of a rise times are less than geometric dimensions of circuit components and therefore its parasitic parameters come out. Thus, it is impossible to match a probe with recorder and exclude an excitation of parasitic circuits. An alternative device in the picosecond range can be considered a probe design where e-beam collector is matched with the cable duct and the whole system operates in the mode of long lines with a traveling wave when possible reflections are moved out in time from the useful signal.

2. Traveling wave collector-type probes

In the simplest version the probe collector can present the edge of the center conductor of 50-Ohm transmitting cable. Such a sensor – the edge of coaxial connector SMA(F) – is shown in Fig. 1, *a*. Here, a picosecond e-beam current is registered in air, fare away with respect to the anode foil of accelerator. It is clear that such a “dot” probe does not ensure the complete collection of e-beam current and can be used only for registering the current envelope. If the central cable connector is extended into the measurement chamber, it is possible an entire spectrum of pulse distortions (Fig. 1, *b–d*) depending on the ratio of the collector section inductance and its capacitance. They are due to excitation of oscillations on parasitic elements (*L* and *C*). If the cable edge is equipped with increased receiving area, it is possible to damp oscillations (Fig. 1, *e*). In this case, we obtain enlargement of the capacitance “radial component”, first of all, capacitance between collector and anode foil. It must be noted, that collector with increased area is already acceptable for measuring an averaged current density of the beam. At the same time, this design requires the transmit time of a signal along collector radial direction would be much less than the pulse rise time. In other words, the area and, corresponding collector capacitance cannot be increased arbitrarily. Otherwise, the broadening of a signal occurs for a short pulses (compare Fig. 1, *a*, and Fig. 1, *e*).

Thus, a collector unit construction is a key question for the picosecond current probe. It should be noted an importance of the probe element mentioned as “anode foil”. In fact, a collector is always advisable to shield by special foil or by fine wire mesh. This makes it possible to keep the parameters of the beam collector constant independently of the probe position with respect to the case elements and the presence or absence of accelerator’s anode foil. Furthermore, in the latter case, when the cathode stands close to the probe, shielding foil removes so-called capacitive component of a signal. Also, the role of a collector as disk antenna sensitive to wide-band electromagnetic interferences anticipating the current pulse that is proper to picosecond high-current circuits is excluded.

[1] The work was supported by the Russian Foundation for Basic Researches (Grants Nos. 07-08-12037 and 08-02-00183).



a	*b*	*c*	*d*	*e*
Rise time is 43 ps Pulsewidth is 55 ps	Rise time is 40 ps (?) Pulsewidth is undefined	Rise time is 40 ps (?) Pulsewidth is 47 ps (?)	Rise time is undefined Pulsewidth is undefined	Rise time is 54 ps Pulsewidth is 91 ps

Fig. 1. Geometry of e-beam current collectors representing a variety of 50-Ohm coaxial cable terminals and corresponding waveforms for the e-beam current pulse representing originally a mono-pulse (pulsewidth < 50 ps; rise time < 35 ps).

3. High time resolution screening probe

Thus, it is actually required the matching of a disk line formed by beam collector and the shielding foil with the nearby section of a coaxial duct. Both these elements are the transmission lines with low impedance providing moderate voltage amplitudes (kilovolt values) with characteristic beam current of about 1 kA. Picosecond electron beam probe (Fig. 2) constructed in accordance with this principle has the highest time resolution. It represents the disk collector (dia. 10 mm) formed by the end of vacuum five-stage stepwise transmission line with 7.3 Ohm input impedance and 50 Ohm output (SMA connector). Input coaxial section with conductor diameters of 12 mm and 10 mm has Teflon isolation. Delay times of all stages of the line including its input section were equal 150 ps. Therefore, signals with up to 300 ps width could be registered at the line output without superposition of reflections.

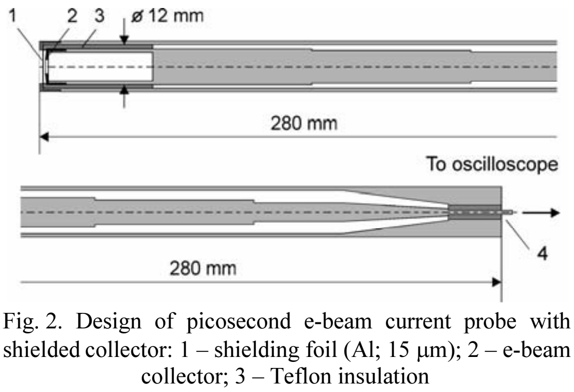


Fig. 2. Design of picosecond e-beam current probe with shielded collector: 1 – shielding foil (Al; 15 μm); 2 – e-beam collector; 3 – Teflon insulation

The beam collector was shielded by aluminum foil (15 μm) or 30 μm wire grid (12X18H10E) with 90% geometric transparency. The "foil-collector" gap and collector conical profile in "*R*-*Z*" coordinates were optimized in the numerical simulations (code KARAT [3]). The final result of optimizations is presented in Fig. 3. Note, that conical collector originally was optimized as the sloping step of the center conductor with coaxial junction "50 Ohm – 7.3 Ohm". Only then the model comparing "rise time" profile of beam current (tubular, paraxial or blank in scale to collector radius) before transit of the foil and the signal – response into 7.3 Ohm coaxial output was used. It was explained, in particular, that conical collector with the central hole should be used for registering tubular beam. It prevents additional rise time pulling. As a result of such optimization the probe ensured the calculated distortion of the current pulse and transfer the corresponding signal along the line with rise time of ~ 20 ps.

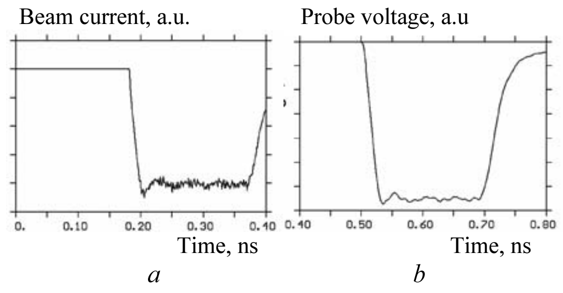


Fig. 3. Shape of e-beam current pulse before shielding foil (*a*) and corresponding voltage pulse (*b*) across output of the first probe's coaxial section possessing an optimized collector geometry (PIC- simulations, code KARAT)

Thin (0.7 mm) disk beam collimator with narrow symmetrical radial slots (0.5 mm) could be placed in front of the collector together with shielding foil. Application of collimator makes it possible to reject coaxial attenuators in the cable duct when it was necessary to compare the current pulses of tubular beam with the amplitude in units and hundreds of amperes with an absolute time reference (Fig. 4). It was typically for comparison of electron diode operation with vacuum and gas isolation. Moreover, the collimator decreases a current down to safe level excepting probable breakdowns of the probe coaxial duct. Otherwise, 1-kA current corresponds to the voltage wave with amplitude of more than 7 kV just in the probe input. Note, also, that with the collimator applied the current probe was connected to the oscilloscope directly by wide-band cable (Times-Microwave SFT-304, the cutoff frequency of 23 GHz) without any additional coaxial connectors. This duct was applied in the measurements with maximum time resolution (Fig. 5, *a*). The pulse rise time (Fig. 5, *a*) on a level of 0.1–0.9 is equal to ~ 34 ps and practically corresponds to the limitation resulting from well-known criteria of dispersion TE wave excitation in the coaxial line.

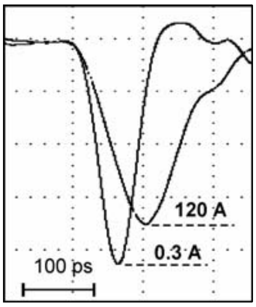
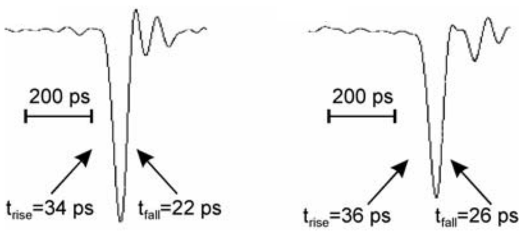


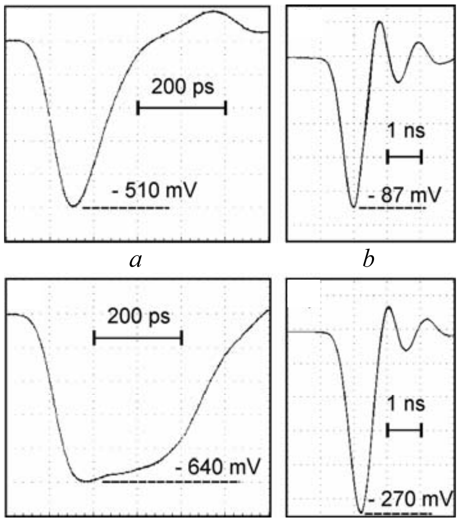
Fig. 4. Beam current pulses recorded for a vacuum (120 A) and air-filled (0.3 A) diode recorded with an absolute time reference



a *b*

Fig. 5. Beam current pulses of ~ 3 A amplitude recorded at the output of air-filled electron diode with an ultimate time resolution (*a*) and in the case when two additional SMA-type connectors were involved in the cable duct (*b*)

Comparing current signals in Fig. 5, it is evident that the use of only one SMA (F) – SMA (F) connector installed between two 1-m-long cables instead of 2-m-long solid cable already leads to the pulse widening to about 2–3 ps (Fig. 5, *b*). It is especially typical for the fall time of the current pulse which must be less than the rise time because of the effect of more effective particle acceleration emitted later with the increased potential on the cathode, as it was investigated in [4]. It is interesting that fall time of the current pulse has a positive burst (Fig. 5, *a*). And the rise time (~ 22 ps) is less than the oscilloscope sampling rate (25 ps) and its certified transient characteristic (~ 28 ps). It confirms the assumption [4] that both the fronts and the duration of the current pulse (Fig. 5) are substantially less than it is recording by the oscilloscope. Actually, in the model measurement we have shown (Fig. 6) that under the conditions when the registering pulse is shorter in comparison with oscilloscope transient time we see the integrated pulse and its envelope interpolation has analogous inverted burst after the fall time. Moreover, amplitude of the burst is as greater as the pulse is shorter in comparison with certified oscilloscope transient characteristic.



c *d*

Fig. 6. *a*; *c* – pulses from the usual test generator, recorded by the oscilloscope TDS6154C (15 GHz, 40 Gs/s) with transient characteristic 28 ps. *b*; *d* – the same pulses recorded by the oscilloscope (500 MHz)

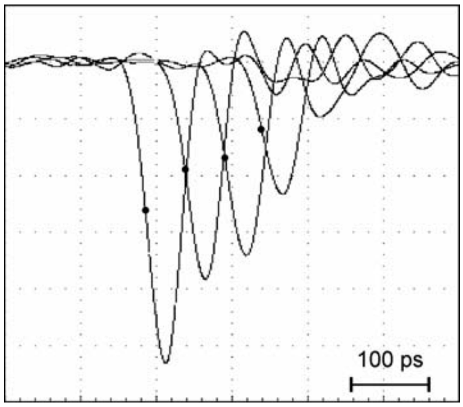


Fig. 7. Recording of e-beam current pulses (~ 3 A) with a probe sequential shifting in the drift channel at divergent axial guiding B-field. Time shifts of 54 ± 2 ps correspond to displacement intervals of 10 mm

It is clear that the current probe with the transient time at the level of 30 ps can be used for the energy estimations of moderately relativistic electrons by time-of-flight method. In case of oscilloscope triggering from the stable rise time of accelerating pulse it is possible to measure the transit time of the beam passing through the section of a drift chamber on the level of "0.5" from the amplitude of the current pulse (Fig. 7). As it follows from oscilloscope traces the energy of the particles of "low-current" e-beam is constant for a free drift in the section of the vacuum channel with a length of 30 mm

4. Conclusion

By using developed current probe the wide range of fundamental investigations of electron beam generation in the atmospheric gap with sharply nonuniform field and the comparison of this regime with the injection of beam by cold cathode under the vacuum conditions was solved [4]. In particular, the duration of e-beam current pulse formed in air-filled diode was estimated from above. Spatial injection area and the moment of the beam formation with respect to the rise time of accelerating voltage pulse were determined, as well as conditions that assign this moment and, correspondingly, the energy of runaway electrons were also explained.

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