doi: 10.56761/EFRE2022.S6-O-029605

Computation of output parameters of a submicrosecond electron accelerator

I.S. Egorov, M.A. Serebrennikov, A.V. Poloskov*

National Research Tomsk Polytechnic University, Tomsk, Russia
egoris@tpu.ru

Abstract. The development of complex systems computational models makes possible the evaluation of their various operation mods with minimal time and resources investment. Including the determination of the system operating parameters ranges, in which their characteristics correspond to the desired ones. This paper presents a submicrosecond electron accelerator computation made in the Multisim electrical process simulation program. The simulated accelerator is based on a high-voltage pulse generator according to the scheme of a high-voltage energy storage device, a pulse transformer, and a vacuum electron diode with an explosive emission cathode. The paper describes the applied methods and approaches of simulation development, the limitations and simplifications used, as well as the simulation error estimation. Based on the created computation, the output electrical parameters of the accelerator were analyzed depending on the amount of stored energy and the parameters of the diode system. The obtained research results can be used in the development of new exemplars of high-voltage pulse technology and for tuning existing accelerators.
Keywords: pulsed electron accelerator, vacuum electron diode, cathode.

1. Introduction

Development of complex physical systems models today is a common approach to the design and testing of equipment, predicting systems performance in different operation modes [1]. This approach makes possible significant reduction of the time and resources spent and, in addition, safe assessment of the equipment performance in critical ranges of operation parameters. At the same time, when creating models of scientific equipment, it is often necessary to describe system elements with node parameters, the characteristics of which are the subject of scientific research and usually are unknown [2, 3]. For example, the characteristics of pulsed vacuum electron diodes based on explosive electron emission [4–6]. The diode impedance is a non-linear value [7], the current value of which depends on many factors: the size of the vacuum gap, the electric field strength in it and its rise rate, the material and morphology of the cathode surface, the geometry of the accelerating gap, and so on. At the moment, a number of the characteristics dependences of the diode on its parameters have been found, for example, the Child-Langmuir law [8], which is fair, taking into account a number of limiting application conditions. However, a universal model of the impedance evolution of such diode, which determines the mode of matching with the generator, is not presented. Thus, simulation the operation of the electrical characteristics of a pulsed accelerator as a whole is a non-trivial task, the solution of which is devoted to this work.

2. Experimental model

In this paper, the electrical characteristics are simulated for a series of repetitive submicrosecond accelerators [9] based on a pulsed transformer [10]. This design of the accelerator uses pulsed charging of a high-voltage capacitive storage, which is switched by a commercially available pseudo-spark switch to a pulsed step-up transformer loaded directly onto a vacuum electron diode. This approach made it possible to create a reliable electrical circuit for generating high-voltage pulses with a repetition rate of up to 100 pps [11].

The simulation of the electrical characteristics of the accelerator operation consisted of simulation of the accelerating voltage pulse and the reaction of the vacuum electron diode, represented as the evolution of the impedance over the duration of the applied voltage pulse. As a software environment for modelling processes in electrical circuits Multisim programme was chosen. Based on the analysis of the principal and elemental schemes of the accelerator, an equivalent circuit was compiled based on the basic elements of electrical circuits for the chosen software. The resulting generator circuit was tested over the entire range of load impedance and showed a high degree of compliance of the simulated characteristics in comparison with real data (Fig.1) [12]. Impedance control was obtained using one diode assembly configuration while changing the cathode-anode gap.

The evolution of the diode impedance during the applying of the accelerating voltage pulse was previously studied in the work [13]. The evolution of the impedance was approximated by linear sections based on the analysis of physical processes occurring in a vacuum electron diode (Fig.2). Another factor that was taken into account when simulating the operation of the accelerator is the capacitive-ohmic characteristics of a sectioned pulse insulator connected in parallel with the load. The analysis of the insulator characteristics is considered in more detail in the work [14]. Thus, the combination of the generator and vacuum electron diode models, taking into account the characteristics of the sectioned pulse insulator, made possible the simulation of the output signals characteristics of the accelerator. The amplitude of the accelerating voltage pulse, the duration of the accelerating voltage pulse, and the energy released in the diode were chosen as the output characteristics.

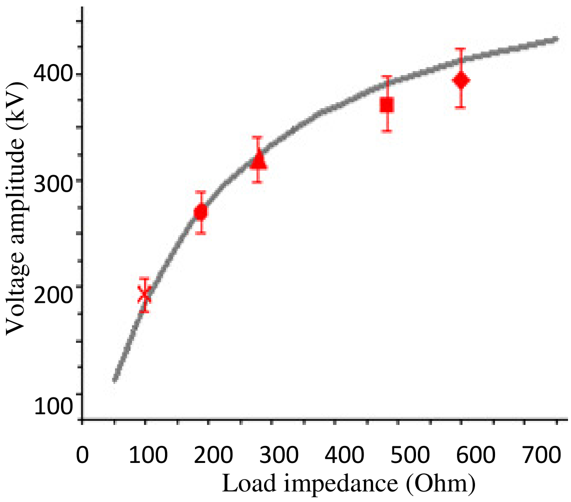

Fig.1. Verification of a high-voltage generator computational model [12]. Simulated curve and empirical data points are compared.

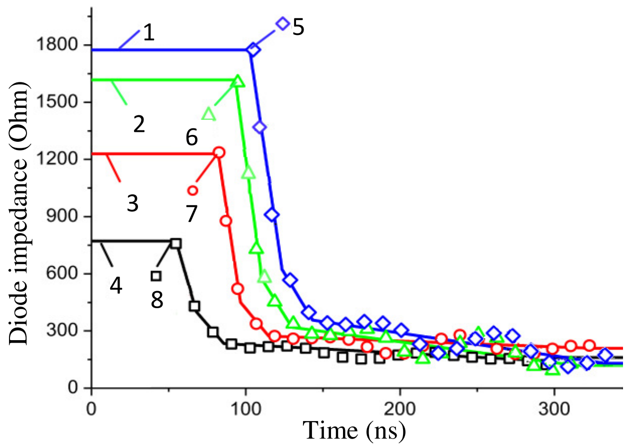

Fig.2. Verification of an impedance computational model for vacuum electron diode [13]. Simulated (1–4) and empirical (58) data are compared.

The circuit solutions used allow modeling in the entire range of element characteristics. At the same time, the construction and use of electron accelerators for solving practical and scientific problems impose a number of physical and engineering restrictions that reduce the range of parameter values in simulation. The accepted limits are listed below.

The duration of the accelerating voltage pulse is less than 1 μs. This limitation was introduced to take into account the operation of the magnetic elements of the system without saturation and to ensure the electrical strength of the insulating elements of the accelerator structure. First of all, a sectioned diode vacuum insulator, which is loaded on at full voltage and operates in difficult conditions of high-intensity pulsed electric fields. In addition, with an increase in the duration of the accelerating voltage pulse, the probability of shorting the accelerating gap and the operation of the vacuum electron diode in the stage of vacuum breakdown increases. In general, for a generator based on a pulsed transformer with a capacitive energy storage, the duration of the voltage pulse at the load is directly proportional to the energy stored in the generator and the load impedance.

One of the most important conditions for the successful operation of a pulsed accelerator with a vacuum electron diode is the preservation of the aperiodic mode of discharging the capacitance of a high-voltage energy storage device. The voltage and current inversion in the accelerating gap often leads to damage to the diode structure and the need to stop beam generation. The experimental values of the load impedance, matched to the generator impedance, were investigated in detail using a high-voltage liquid resistor [15]. The impedance at the time of the current maximum was taken as the impedance value for modeling.

When using an accelerator with beam extraction into the atmosphere, electrons with energies less than 100 keV will be absorbed by the exit window membrane (Ti 60 µm). The efficiency of electron beam energy extraction at different amplitudes of accelerating voltage pulses was obtained experimentally and taken into account in assessing the overall efficiency of the accelerator. When simulating the operation of the generator on an internal target, the energy supplied to the diode was considered effective. The efficiency of energy transfer between the compression stages in the generator was obtained experimentally. Energy losses during the formation and injection into the atmosphere of a beam with a wide spectrum of electron kinetic energies require additional studies. In the framework of this work, energy losses were taken into account on the basis of experimental data for a titanium membrane of the output window with a thickness of 60 µm. The maximum value of the accelerating voltage pulse amplitude was limited to 500 kV. This restriction was added taking into account the requirements of state regulation of the use of ionizing radiation sources and the possibility of using built-in biological protection.

3. Test results and discussion

The results of the experimental evaluation of the efficiency of transferring the accumulated energy into the energy of the electron beam are shown in Fig.3. The curve is extrapolated by a polynomial of the second degree to estimate the function outside the operating parameters of the created installations. An analysis of the beam generation efficiency curve (Fig.3) shows the benefit of creating accelerators with a generator based on a pulse transformer with an accelerating voltage level of more than 400 kV. This conclusion is consistent with existing ideas about the energy losses of the beam during its extraction into the atmosphere, as well as the reduction in the specific value of energy losses in the energy compression stages. Increasing the voltage while maintaining the dimensions of the installation will lead to an increase in the electric field strength in insulating units, which requires that the accelerator reliability and service life be taken into account in the assessment.

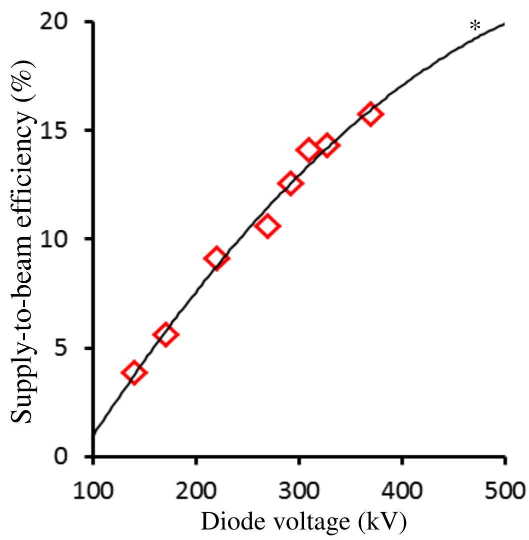

Fig.3. Empirical supply-to-beam efficiency (%). Sign * marks 20% value aproximated.

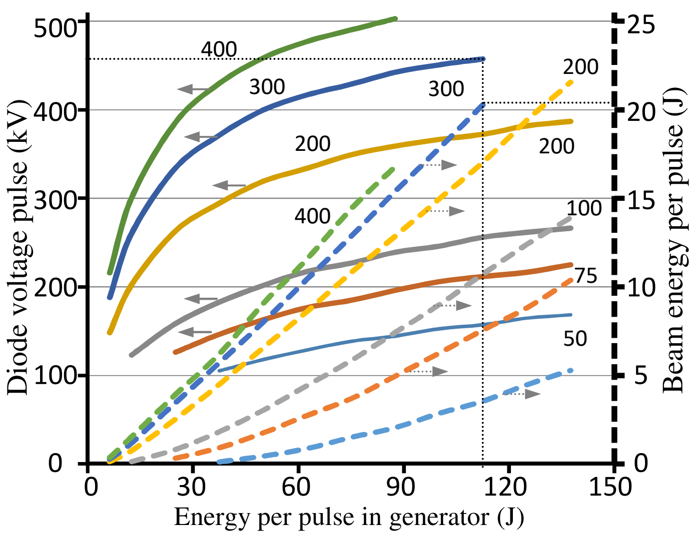

Fig.4. Computated load-energy diagram for accelerator line. Load impedances are given in Ohms.

Based on the computational model of the accelerator, a diagram was constructed linking the energy reserve in the generator with the voltage value in the load and the energy transferred by the electron beam to the atmosphere (Fig.4). The diagram includes the entire range of installation parameters, subject to the restrictions listed above. The analysis of the diagram makes it possible to adjust both existing accelerator samples and to make a quick preliminary assessment of the characteristics of installations before designing.

The degree of influence of the load, both on the diode voltage level and on the generation efficiency as a whole should be noted. The transformer connection between the generator and the load determines the quadratic dependence of the listed characteristics. This fact recommends giving preference to the generator operating modes with a high-resistance load, which increases the duration of the generator voltage pulse. At the same time, the transformer limits the power flow to the load through the material and cross section of the magnetic circuit, expressed in core saturation time ($V \cdot s$).

Using the computational model of the accelerator, the operating mode with the maximum efficiency of beam generation can be found from the diagram in Fig.4 by dividing the energy transferred by the beam into the atmosphere by the energy stored in the generator. The maximum value of about 20% is achieved with a load impedance of about 300 Ohm, with a diode voltage of about 450 kV, allowing more than 20 J/pulse to be output. Increasing the impedance to 400 Ω leads to an increase in the voltage pulse duration over 1 μs already for a storage device storing 90 J.

To further increase the energy stored in the generator while maintaining the duration of the voltage pulse, a significant decrease in the inductance of the transformer in the output circuit of the discharge circuit is required. Fulfillment of this requirement while maintaining the electrical strength of the structure will lead to an increase in weight and size characteristics. Another area of work is to reduce energy losses during the generation and extraction of an electron beam into the atmosphere.

4. Conclusion

As a result of the work, a computational model of a submicrosecond electron accelerator has been developed and analyzed. The simulated accelerator is based on a high-voltage pulse generator according to the scheme of a high-voltage energy storage device, a pulse transformer, and a vacuum electron diode with an explosive emission cathode. Highest efficiency of 20 % was found for the following range of accelerator parameters: 100–500 kV, 6–138 J/pulse in generator and less than 1 μs of aperiodic voltage pulse duration. Results will be used both for adjusting accelerators in use and for future developments.

Acknowledgements

The authors are grateful to National Research Tomsk Polytechnic University (TPU, Russia) for technical support in a case of TPU development program. The work was conducted within the framework of the state assignment in the field of scientific activity: No. FSWW-2020-0008.

5. References

[1] Sandve G.K., Nekrutenko A., Taylor J., Hovig E., *PLoS Computational Biology*, **9**, e1003285, 2013; doi: 10.1371/journal.pcbi.1003285

[2] Peled D., Vardi M., Yannakakis M., *Formal Methods for Protocol Engineering and Distributed Systems*, **225**, 1999; doi: 10.1007/978-0-387-35578-8_13

[3] Ljung L., *IEEE Proceedings of the 18th IEEE Instrumentation and Measurement Technology Conference*, **138**, 2001; doi: 10.1109/IMTC.2001.928802

[4] Bugaev S.P., Litvinov E.A., Mesyats G.A., Proskurovskiĭ D.I., *Soviet Physics Uspekhi*, **18**, 51, 1975; doi: 10.1070/PU1975v018n01ABEH004693

[5] Roy A., Patel A., Menon R., Sharma A., Chakravarthy D.P., Patil D.S., *Physics of Plasmas*, **18**, 103108, 2011; doi: 10.1063/1.3646361
[6] Krasik Y.E., Dunaevsky A., Krokhmal A., Felsteiner J., Gunin A.V., Pegel I.V., Korovin S.D., *Journal of Applied Physics*, **89**, 2379, 2001; doi: 10.1063/1.1337924
[7] Roy A., Menon R., Singh S.K., Kulkarni M.R., Saroj P.C., Nagesh K. V., Mittal K.C., Chakravarthy D.P., *Physics of Plasmas*, **16**, 033113, 2009; doi: 10.1063/1.3097903
[8] Yadavalli S.V., Bollen R.L., *Nuclear Instruments and Methods*, **75**, 229, 1969; doi: 10.1016/0029-554X(69)90600-4
[9] Remnev G., Egorov I., Kaikanov M., Kanaev G., Lukonin E., Nashilevskiy A., Stepanov A., *Izvestiya Vysshih Uchebnyh Zavedenij. Fizika, (in Russian)*, **54**(11/3), 74, 2011; url: https://www.elibrary.ru/item.asp?id=17650587
[10] Poloskov A., Egorov I., Nashilevskiy A., Ezhov V., Smolyanskiy E., Serebrennikov M., Remnev G., *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, **969**, 163951, 2020; doi: 10.1016/j.nima.2020.163951.
[11] Remnev G.E., Egorov I.S., Kaikanov M.I., Kanaev G., Lukonin E.I., Nashilevsky A.V., Stepanov A.V., *Nuclear and Radiation Physics. 8th International Conference: Reports (in Russian),* 549, 2011;
[12] Egorov I., *Review of Scientific Instruments*, **85**, 066112, 2014; doi: 10.1063/1.4884895
[13] Egorov I., Poloskov A., Remnev G., *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, **921**, 68, 2019; doi: 10.1016/j.nima.2018.12.008
[14] Egorov I., *IEEE Transactions on Dielectrics and Electrical Insulation*, **23**, 2174, 2016; doi: 10.1109/TDEI.2016.7556492
[15] Poloskov A.V., Egorov I.S., Serebrennikov M.A., *Journal of Physics: Conference Series*, **830**, 012047, 2017; doi: 10.1088/1742-6596/830/1/012047