result in the space between the strips there is alternating, dying away magnet field along the radius. The strips convexity in width gives the field force lines a «barrel-like» form typical for the focusing («betatron») field.

All four sections of the single-turn winding form a synchrotron single magnet system. Sections of the single-turn winding connected with vacuum seals – 5 along the strip edges – 2, 3 form four curvilinear sections of accelerating chamber combined with magnetizing single-turn winding.

These curvilinear sections are connected with each other by straight electron wires and form a closed chamber as it is done in the known synchrotrons of «racetrack» type. The straight sections of the accelerating chamber free from magnet field are used to assemble the attendant equipment – resonators, vacuum pumps etc.

The value of control magnet field strength in the accelerator orbit depends on energy of the accelerated particles; the maximum field strength is determined by setting value of particle energy that is desired to obtain. Injection of the charged particles into accelerating chamber is made by the injector – 7, particle acceleration – by means of resonator or resonators – 8, vacuum in the chamber is provided by the pumps – 9.

Thus, the use of single-turn winding concept for induction of control magnet field (similar to single-turn winding used in miniature induction cyclic accelerator [4]) in the form of four similar sections located in circular sectors of the accelerated particle path, at simultaneous performing of the winding the function of accelerating chamber results in creation of charged particle accelerator of new type, i.e. iron-free synchrotron having a number of new technical and engineering-economical parameters, such as small weight of the accelerator and the accelerating chamber, combination of magnetizing winding and accelerating chamber functions in a single system, simplified technology of the accelerator production and assembling and etc. Therefore, the suggested iron-free synchrotron is favourably distinguished from all the known accelerators of such type.

REFERENCE

1. Electron synchrotron «Sirius» // Formation and Development of Scientific Schools in Tomsk Polytechnic University / Edited by Yu.P. Pokholkov, V.Ya. Ushakov. – Tomsk, 1996. – P. 158–160.
2. Vorobyev A.A., Chuchalin I.P., Vlasov A.G. et al. TPI Synchrotron per 1,5 GeV. – Moscow: Atomizdat, 1968. – 160 p.
3. Pat. 2265974 RF. IPC H05H 13/04. Iron-free synchrotron / V.A. Moskalev. Published 10.02.2005, Bull. № 34.
4. Pat. 2193829 RF. IPC H05H 11/00. Induction charged particle accelerator / V.A. Moskalev. Published 27.11.2002, Bull. № 33.

Arrived on 21.04.2006

UDC 621.384.647

RESEARCH OF CHARGE BALANCE IN DIODE UNIT OF PULSED ELECTRON ACCELERATOR

A.I. Pushkarev, R.V. Sazonov

High Voltage Research Institute, Tomsk
E-mail: aipush@mail.ru

The results of experimental research of charge balance in the diode unit of high-current pulsed electron accelerator TEU-500 (350...500 keV, 60 ns, 250 J per pulse) at the operation of electron beam generation are presented. The investigations are performed for the planar diode as with the cathodes made of graphite, copper, carbon fiber 43...60 mm in diameter so with the multi-edge cathode. It is shown that the main source of parasite losses of electrons in the planar diode is their scattering in the anode-cathode gap induced by the electron field distortion at the cathode periphery. In the matching mode of diode impedance to the output resistance of nanosecond generator (gap of 10...12 mm) the charge losses value does not exceed 12 %. The half of electron scattering angle is 68° at small anode-cathode gaps and it decreases with the gap increase down to 60°.

Introduction

The application of pulsed electron beam for the initiation of plasmachemical processes, gas laser injection, microwave radiation generation and other fields requires the development of efficient electron accelerator which would possess long operation life time and high stability of operation parameters. Any nonproductive energy losses lead to the heating and premature destruction of construction units of the accelerator. The experimental investigations performed by us and the analysis of work of other authors [1, 2] showed that the accelerator operation life time is mainly determined by the diode unit.

The presence of nonproductive losses in the diode unit can be calculated by the current balance. The total current introduced to the diode unit from the nanosecond generator is equal to the sum of extracted electron beam current, current of capacity charge exchange of the diode unit and parasite losses current. The losses during the electron beam generation can be conditioned either by the electron beam scattering while going from the cathode to the Faraday cup collector or by the charge escape along the isolator surface, or by the parasite discharges in the vacuum volume of the diode chamber. One of the principal loss sources in the diode is the electron scattering. In [3] it is shown that the electrons in the anode-cathode gap scatter to the half angle of more than 40° at the absence of external driving magnetic filed. While creating the diode unit it is necessary to take into consideration the electron scattering in order to prevent the parasite losses.

At the analysis of current balance in the diode unit for the capacity current calculation by the following correlation

$$I_c = C\frac{dU_{емк}}{dt}$$

it is necessary to perform the differentiation of signals from the voltage divider. But at that the wide data spread appears what requires evening. The evening leads to the displacement of calculated dependences fronts that makes the data interpretation more difficult. The calculation of charge change in the accelerator diode unit at the electron beam generation has been performed in order to remove the evenning operation. The purpose of the performed work is to investigate charge balance in the diode unit of the accelerator during the electron beam generation for the determination of parasite loss sources of the consumed current and the construction optimization.

1. Experimental

The experiments were performed at the pulsed electron accelerator TEU-500 (350...500 kV, 60 ns, sum kinetics energy of electrons per pulse was up to 250 J) [4, 5]. The pulse rate in the experiments was 0.5...1 pulse per second.

The peculiarity of the accelerator construction is the use of step-up transformer inserted between the double forming line (DFL) and the diode. The transformer core saturation during the DFL charging allowed significantly decreasing the pre-pulse amplitude and its action on the diode operation without the peaking discharger application. In case of premature demagnetization of matching transformer core the voltage pulse shape formed by the nanosecond generator (DFL and transformer) is close to the optimal one and it compensates the diode impedance decrease due to the explosion emission plasma spread [6]. This allows matching the diode to the generator during the electron beam generation.

For the measurement of current flowing in the nanosecond generator load the Rogowski coil (RC) was used. For the voltage measurement the capacitor divider placed in the oil-filled chamber was used. The total current of the electron beam was measured by the Faraday cup (FC). FC was pumped out together with the diode chamber up to the pressure not more than 0,05 Pa. For the temporary binding of electric signals the special measurements in the short-circuit mode at the operation to the resistance load and at the electron beam generation were performed. The inaccuracy of time binding of electric signals did not exceed 0,5 ns. The calibration of the diagnostic equipment showed that it correctly reflects the accelerator operation in the short-circuit mode (U=50...60 kV) at the operation to the resistance load up to 60 Ohm (U=150...200 kV) or to the planar diode (U=350...500 kV). The accuracy of measurement of voltage, diode current, frequency characteristics of diagnostics equipment allow calculating the charge variation in the diode unit with the inaccuracy of no worse than 10 %.

The investigations were performed for the planar configuration of the diode with planar cathode 43...60 mm in diameter. The FC planar collector 92 mm in diameter was used as an anode. Fig. 1 represents the oscillograms of voltage applied to the diode and electron beam current measured by FC. The oscillograms are averaged over 10 serial pulses going with 0.5-Hz frequency rate.

2. Research of charge loss variation in accelerator diode unit during electron beam generation

Both the increase of charge input to the diode unit from the nanosecond generator and the charge transferred by the electron beam were calculated by the integration of total current consumed by the diode unit and electron beam current correspondently. The charge of the diode unit capacity equals the multiplication of the capacity and the voltage value.

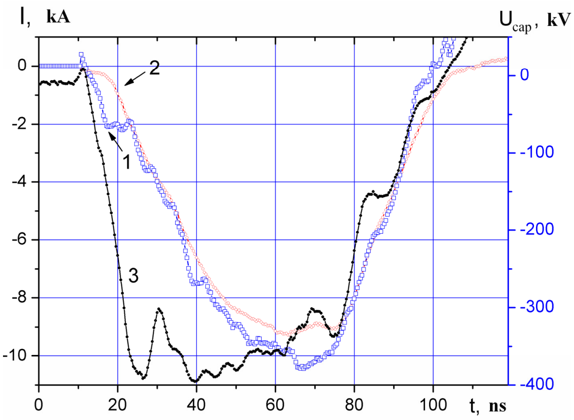

Fig. 1. *The oscillograms: 1) of total diode current, 2) of electron beam current, 3) of voltage applied to the planar diode. The cathode is 45 mm in diameter, made of graphite, with 10.5 mm gap*

Fig. 2 shows the variation of charge going to the diode unit from the nanosecond generator, the charge of diode unit capacity and charge transferred by the extracted electron beam during the electron beam generation. Fig. 2 represents also the charge losses in the diode unit equal to the difference of the charge going from the generator and the charges of the extracted electron beam and diode unit capacity.

To find the charge loss source in the diode unit the measurements of charge balance at the various values of anode-cathode gap were performed. Fig. 3 shows the temporary dependences of charge losses during the electron beam generation at the various gaps. The charge losses value is rated to the value of total charge applied to the diode from the generator by the pulse end. In the matching mode of the diode impedance and resistance output of nanosecond generator (gap of 10...12 mm) the charge loss value did not exceed 12 %. During the electron beam formation the charge losses increase linearly because they can be connected to the electron beam scattering. Similar dependences of charge losses variations during the electron beam generation are obtained for the cathodes made of carbon fiber, copper, for multi-edge copper or tungsten cathodes.

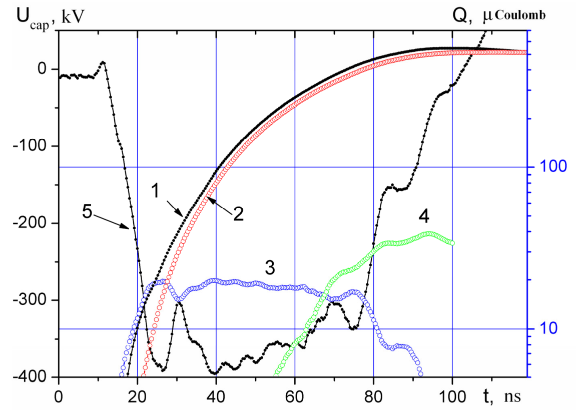

Fig. 2. *The charge balance in the diode unit during electron beam generation: 1) charge introduced from the nanosecond generator, 2) charge transferred by the electron beam, 3) charge in the diode unit capacity, 4) charge losses, 5) voltage at the generator output. The cathode is 45 mm in diameter, made of graphite, with 10.5-mm gap*

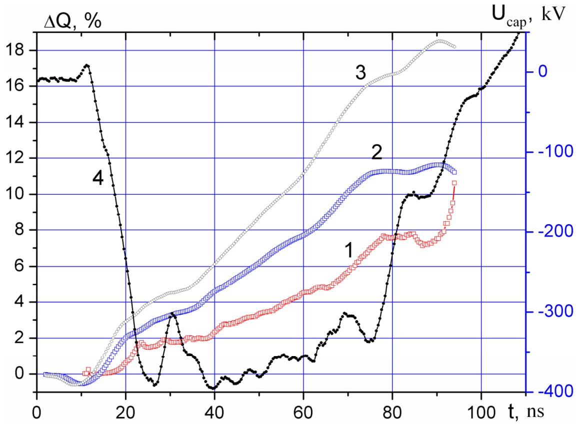

Fig. 3. *The charge losses variation (rated to the total charge applied from the nanosecond generator) during the electron beam formation for the various anode-cathode gaps: 1) 10,5, 2) 12, 3) 15 mm. The dependence 4 is voltage applied to the diode. The cathode is 45 mm in diameter, made of graphite*

3. Investigation of total charge losses by the end of main voltage pulse

To find the losses source in the accelerator diode unit also the measurements of charge losses by the voltage pulse end (total losses) for the various anode-cathode gaps were performed. Fig. 4 shows the dependence of total charge losses in the diode unit on the gap size for the diode with graphite cathodes of various diameters. The losses are rated to the value of charge received from the nanosecond generator for the voltage pulse time. It was found out that the charge losses do not appear unless the gap is larger than 9 mm. The increase of charge losses simultaneously with the gap increase in the diode also proves that these losses are connected to the electron beam scattering. Additional charge losses in the accelerator diode unit besides the electron beam scattering losses are insignificant.

The investigations of energy density distribution in the cross section by the dosimetric film [7] showed that the average energy density of electron beam at the output of planar diode (behind the anode mesh) changes insignificantly.

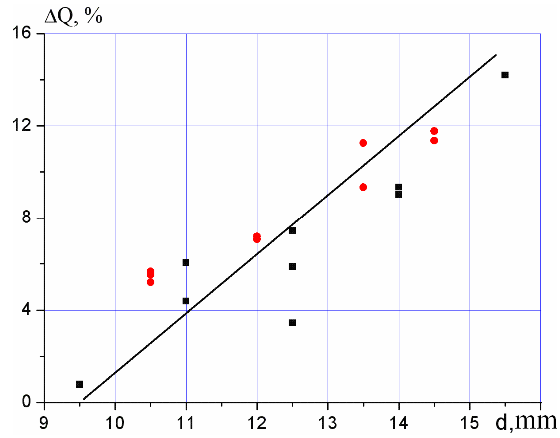

Fig. 4. *The charge losses dependence in the diode unit on the anode-cathode gap. The cathode is 45 mm (■) and 60 mm (o) in diameter, made of graphite*

Let us assume that the electron density is also the same along the cross section area. In this case the decrease of the electron number going to the FC collector with the increase of the cathode-collector distance d equals the difference of cross section area of electron beams (at the expansion to the scattering angle β after passing through the distance d) and FC collector area. At that the charge losses are equal to

$$\Delta Q = q\Delta N = qj\Delta S = qj(\pi(r_к + d\,\mathrm{tg}\beta)^2 - S_{цф}),$$

where q is electron charge, j is electron beam density in the cross section (in FC plane), r_c is cathode radius, S_{FC} is FC collector area.

The total charge of electron beam registered by FC can be written down in the following view:

$$Q_e = qjS_{цф}.$$

The relative value of charge losses of electron beam is

$$\frac{\Delta Q}{Q_e} = \frac{\pi(r_к + d\cdot\mathrm{tg}\beta)^2 - S_{цф}}{S_{цф}} = \left(\frac{r_к + d\cdot\mathrm{tg}\beta}{r_{цф}}\right)^2 - 1,$$

where r_{FC} is FC collector radius.

Then

$$\mathrm{tg}\beta = \frac{1}{d}\cdot\left(r_{цф}\cdot\sqrt{\left(\frac{\Delta Q}{Q_e}+1\right)} - r_к\right). \quad (1)$$

Fig. 5 shows the dependence of scattering angle of the electron beam on the anode-cathode gap for the various cathodes. The calculations are performed in the relation to (1). The data of fig. 5 correspond to the diode with cathodes 43...60 mm in diameter made of various materials.

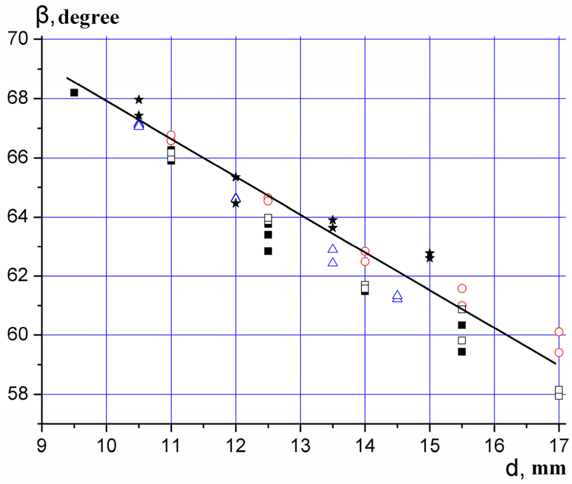

Fig. 5. *The dependences of electron scattering angle on the anode-cathode gap size. The cathodes made of graphite (45 mm (■) and 60 mm (*)), multi-edge (43 mm (o)), carbon fiber (45 mm (Δ)) and needle (43 mm (□)) were used*

The change of propagation path of electron movement in the anode-cathode gap of planar diode can be conditioned by the electric filed distortion at the cathode periphery, by the proper magnetic field of beam current and by the electrostatic electron beam repulsion. In the last two cases the value of electron scattering angle would depend on the beam current. The investigations of the influence of total charge transferred by the electron beam on the electron scattering angle were performed (Fig. 6).

The investigation showed that the electron scattering angle within the calculation accuracy does not depend on the total charge value of electron beam. That is why the main source of electron scattering in the diode is the electron field distortion at the cathode periphery.

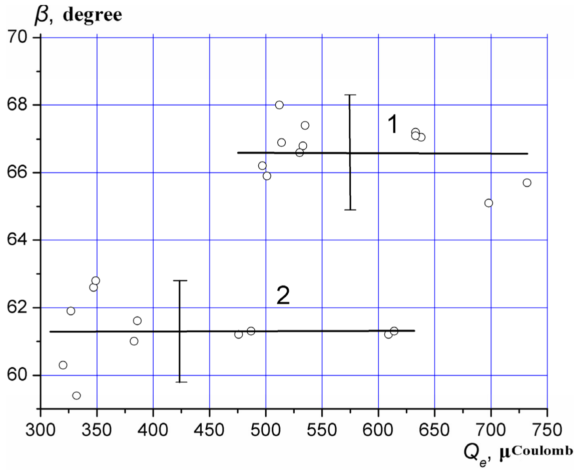

Fig. 6. *The dependence of electron scattering angle on the total charge of electron beam in the gaps of: 1) 10.5...11 mm; 2) 14.5...15.5 mm. The cathode was 43...60 mm in diameter made of various materials*

Conclusion

The performed investigations of the charge balance of the electron accelerator diode unit showed that the main source of parasite losses of electrons in the planar diode is their scattering in the anode-cathode gap conditioned by the electric field distortion at the cathode periphery. In the mode of diode impedance matching to the output resistance of the nanosecond generator the charge losses value is 68° at smaller gaps and it decreases with the increase of the gap down to 60°. The values of electron scattering angle are obtained under the condition of electron current density uniformity and they correspond to the maximal scattering angle. At the current density decrease to the electron beam periphery the main part of electrons are distributed within the range of smaller angle. The obtained values of electron scattering angle can be used while creating the anode unit of the accelerator.

The work has been supported by RFBR, grants № 06-08-00147 and 06-03-46002.

REFERENCES

1. Mesyats G.A. Pulsed energy and electronics. – M.: Nauka, 2004. – 704 p.
2. Sokovnin S.Yu., Kotov Yu.A., Balezin M.E. Frequency nanosecond electron acceleraotrs UPT Type // Radiation Physics and Chemistry of Inorganic Materials: Proc. of the 12th Intern. Conf. – Tomsk, September 23–27, 2003. – P. 428–430.
3. Parker R.K., Anderson R.E., Duncan C.V. Plasma-induced field emission and the characteristics of high-current relativistic electron flow // Journal of Applied Physics. – 1974. – V. 4. – № 6. – P. 2463–2479.
4. Remnev G.E., Furman E.G., Pushkarev A.I., Karpuzov S.B., Kondratiev N.A., Goncharov D.V. Pulsed high-current accelerator with matching transformer // Devices and Experiment Technique. – 2004. – № 3. – P. 130–134.
5. Patent on IM 41951 RF. IPC7 H05H 5/08. Pulsed Electron Accelerator / D.V. Goncharov, G.E. Remnev, A.I. Pushkarev, E.G. Furman. Applied June 15, 2004, published November 10, 2004, bulletin. № 31.
6. Remnev G.E., Pushkarev A.I., Furman E.G. Matching of double formaind line with explosive emission cathode // Letters to Technical Physics Journal. – 2004. – V. 30. – № 14. – P. 63–67.
7. Goncharov D.V., Ezhov V.V., Pushkarev A.I., Remnev G.E. Research of energy density distribution of high-current pulsed electron beam // Bulletin of Tomsk Polytechnic University. – 2005. – V. 308. – № 6. – P. 76–80.

Arrived on 06.09.2006