Vacuum xxx (2017) 1–5

Contents lists available at ScienceDirect

Vacuum

journal homepage: www.elsevier.com/locate/vacuum

Effect of emission current delay on the efficiency of electron beam production

Ivan Egorov*, Gennady Remnev, Artem Poloskov, Maksim Serebrennikov

Tomsk Polytechnic University, 634050, Tomsk, Lenin ave. 30, Russian Federation

A R T I C L E I N F O

Article history:
Received 24 December 2016
Accepted 21 March 2017
Available online xxx

Keywords:
Cathode
Vacuum electron diode
Electron emission current
Accelerator efficiency

A B S T R A C T

The vacuum diode of an ASTRA-M pulsed electron accelerator with cathodes providing various delay times of the emission current from the beginning of the accelerating voltage pulse was tested. The long delay times of the emission current raised the maximum value of the accelerating voltage pulse and the value of average electron kinetic energy. As a result, the ejected beam energy-loss decreased, while the total accelerator efficiency increased.

1. Introduction

An electron beam with its unique application properties is a modern tool, which is widely used in industry, medicine, and science. A great deal of scientific research applications requires precise beam parameters such as good reproducibility and a specially selected electron kinetic energy spectrum [1–3]. Sources of "precision beams" are unique and complicated accelerators, which are explored by scientific institutions and maintained by highly-proficient support staff. At the same time, there are some well-known applications, such as gas and water treatment, which require electron beams with a wide range of parameters. For those applications, the treatment effect can be easily described by an absorbed dose [4–6]. Cheap and simple accelerators seem to be better for such applications. In this case, the pulsed electron accelerators should be compact and adopted for low power local applications by improving their insulator characteristics for short voltage pulses [7,8]. One of the simplest versions is a transformer-based accelerator with a capacitive energy bank [9,10]. The accelerator described in Ref. [11] uses a manufactured high voltage switcher with unique operation characteristics [12] for a self-triggered commutation of capacitive energy bank [13] directly to the vacuum electron diode through the pulsed transformer. The pulsed transformer generates a bell-shaped accelerating voltage pulse. Therefore, some electrons of the beam have very low kinetic energies to be ejected through an exit membrane.

The Astra-M accelerator with a diode resembling a cathode made of composite metal-ceramic material has been tested [14]. The accelerator tests revealed that introduction of the composite cathode caused a delay of tens of nanoseconds from the arrival of the diode voltage pulse until the electron emission current rise. At atmospheric pressure inside the reaction chamber, the composite cathode demonstrated better beam injection efficiency in comparison with a multipoint copper cathode, which featured a shorter delay time of the emission current. A titanium foil of 60 μm thickness was used as a membrane for an exit window. Similar results on the increased efficiency were described in Ref. [15] where an accelerator with inductive energy storage was used [16]. Authors of [17] reported that the delay of emission current depended on the capacity of the ceramics and the electric field strength in the accelerating gap and in the area of cathode surface.

In this paper, we present and analyze the results of experimental tests for various accelerating gaps and various cathode materials. The paper also aims to study an effect of increased beam ejection efficiency for the ASTRA-M accelerator.

2. Materials and methods

The installation for the experimental tests comprised the diode system and the diagnostics of the ASTRA-M accelerator [11]. The accuracy of the diagnostics for voltage and current waveforms is better than 90%. The installation is schematically shown in Fig. 1. The cathode fixture enabled us to set the cathode-anode gap

* Corresponding author.
E-mail address: egoris@tpu.ru (I. Egorov).

http://dx.doi.org/10.1016/j.vacuum.2017.03.030
0042-207X/© 2017 Published by Elsevier Ltd.

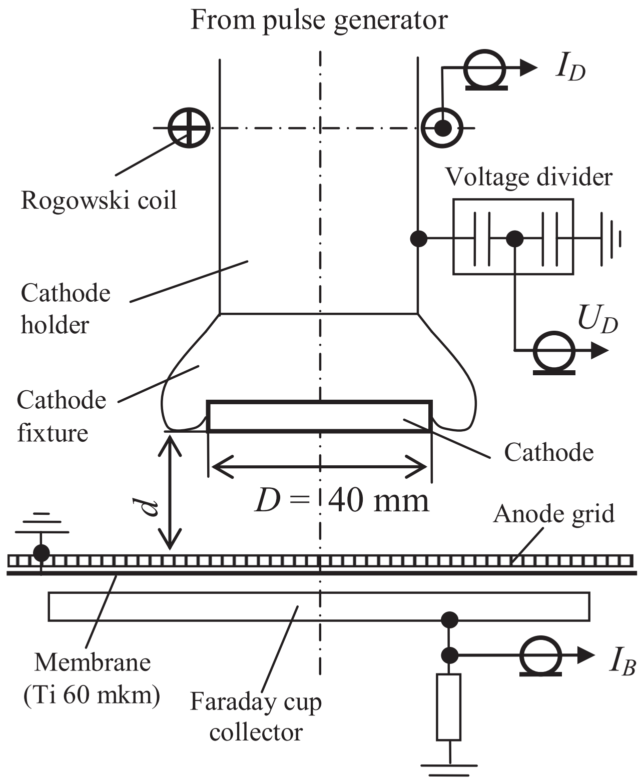

Fig. 1. Schematic diagram of experimental system.

d equal to 16 mm and 20 mm. The planar cathodes, made of various materials, were tested with the same geometry of vacuum diodes. All of them were 40 mm in diameter and had rounded edges. We tested a multipoint cathode made of a copper cable braiding (a wire diameter was 0.1 mm), a graphite cathode and two types of composite cathodes.

Various ceramic inclusions of: 50 vol% of $CuBaTiO_3$ (<125 μm) for 24% porosity copper matrix and 30 vol% of Al_2O_3 (50–125 μm) for 42% porosity copper matrix were incorporated into the composite cathodes. Matrices of both cathodes were manufactured by sintering the pressed ceramic-copper powders at 1000 °C temperature, for 1 h [14].

For all tests, the generator of accelerating voltage pulses operated under the same mode. The generator parameters were controlled from pulse to pulse by monitoring the diode voltage and the total diode current. The typical waveforms of the diode voltage and the emission current were obtained by averaging 16 serial pulses after more than 100 probing shots. To measure the total energy transferred by an electron beam through the anode grid (of 92% transparency) and exit window membrane, the Faraday cup collector was replaced by a collector in the form of a calorimeter (Fig. 1). In our experimental setup, the total electron emission current was registered without the exit window membrane (i.e. the anode grid was used only). Dosimetry films of the POR type were used for every experiment for fast analysis of energy density distribution of the electron beam [18]. Tapes of dosimetry films were fixed in the cross-section of the beam through the exit window center axis.

3. Results and discussion

Fig. 2a–c shows typical curves of voltage and current signals for various cathodes and 20 mm accelerating gap. Fig. 2d shows an example of the data obtained for a Cu + $BaTiO_3$ cathode. The current delay time T_{del} was calculated as a time difference between 0.1 levels of the accelerating voltage pulse and the electron beam current pulse.

A comparison of the obtained data for all cathodes, which are shown in Fig. 2a–c, demonstrates different maxima of the accelerating voltage pulses due to varying delay times of the emission current. The voltage curves rose equally until the emission current started to rise with the rate of up to $4 \cdot 10^{12}$ V/s (Fig. 2a). The electron beam current was ejected outside (Fig. 2c) through a 60 mkm Ti foil. Its values differed for various samples since the kinetic energy of beam electrons during the accelerating voltage pulse also differed, while the total current amplitudes remained the same. This difference in the voltage and the total diode current (Fig. 2a and b) clearly illustrates changes occurring in the discharge mode of the capacitive energy bank of pulse generator. Thus, the voltage waveform of the $CuBaTiO_3$ cathode sample shows an aperiodic discharge of the energy bank, which means non-matched mode of the generator load [19]. A non-matched regime decreases the efficiency of a pulsed high voltage transformer and can cause overvoltage damage of the transformer output windings of the high-voltage insulator of the electron gun [20].

For repetitive operation of the vacuum electron diode, the worst mode is a deep periodic discharge, which is illustrated in Fig. 2a for the copper multipoint cathode. The energy of the positive part of voltage curve cannot be used for acceleration of electrons, but it can cause additional heating of the diode and favorable conditions for breakdown of the accelerating gap or breakdowns of the solid dielectric [20,21].

The spectra of the electron kinetic energy (Fig. 3) were calculated using the data of Fig. 2a and b. The electron kinetic energy spectra were calculated by dividing the charge of the selected range by the total charge of the beam. An average value of the electron kinetic energy was calculated for every cathode sample as a mathematic prediction of the kinetic energy spectrum.

The data obtained and calculated for various cathodes and accelerating gaps are summarized in Table 1. In all experiments, the delay time of the emission current became longer as the gap became wider.

The increase of the delay time resulted in higher values of the output energy of the ejected beam. This occurred because the increasing average kinetic energy of beam electrons resulted in a decrease of energy loss in the exit window membrane. The above described results are illustrated in Fig. 4.

In Table 1, the row entitled "*Beam pulse energy before the foil*" summarizes the fluctuations of energy transferred from generator to the beam. The fluctuation seems to be a result of varying matching conditions between the generator and the load impedance. The dependence of the generator efficiency on the delay time of the load (diode) current will be the subject of future research.

Fig. 4 shows that the value of the output energy of the ejected electron beam provided by the graphite cathode is close to that of the composite cathode, however the delay time of the emission current is shorter. It seems to be due to a maximum density of emission points on the cathode surface. Verification of this hypothesis is also a subject of future research.

Both composite cathodes demonstrated a maximum value of outside-ejected energy equal to 9 J (See Table 1). The cathode Cu + Al_2O_3 produced the highest total current. The cathode Cu + $BaTiO_3$ showed a decrease of loss due to the higher average kinetic energy of beam electrons.

Imprints of the electron beam in dosimetry films (Fig. 5) showed that the uniformity of the electron beam energy [18] is better than 75% for the exit window diameter.