Source of Pulsed Electron and Ion Beams Based on the Nanosecond Voltage Generator with Matching Transformer

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Abstract - The construction of nanosecond voltage generator with the matching transformer and forced care demagnetization prior to the voltage pulse formation is presented in the article. Based on the developed generator the source of nanosecond electron beam was created. The electron beam has the following parameters: electron kinetic energy is 450…500 keV, beam current is 6 kA; pulse duration at the half-height is 60 ns. The generator is also used to form pulsed ion beam with the following parameters: ion current density is ~600 A/cm^2, energy density is ~11 J/cm^2, potential at the anode is 300…350 kV. The ion diode construction without prior plasma formation is also described in the report.

1. Introduction

Electron beams of nanosecond duration, with currents of more than 5 kA and hundreds-of-keV energy are of great interest for a number of applied researches in the field of radiation chemistry, plasma chemistry, generation of intensive microwave radiation and others [1]. Pulsed ion beams are used to modify and harden the surface layer of cutting tools, surface preparation in order to apply wear-resistant coatings.

Either ordinary or double forming lines (DFL) based on deionized water, transformer oil or compressed gas are most commonly used for accelerating-voltage formation in the high-current pulsed accelerators of electrons or ions [1]. In order to generate beams with the energy of more than 100 J the use of DFL based on deionized water is preferable. High dielectric water penetrability provides a significant decrease of sizes of DFL and the accelerator in general. But the impedance of DFL based on deionized water is less than 10 Ohm that is why the problem of DFL-diode matching appears because the diode impedance is significantly higher that the line impedance. In the work [2] it is offered to use a set-up transformer for matching. But the authors note that the formation of voltage pulse (pre-pulse) takes place at the transformer load (diode) during DFL charging. The pre-pulse can reach up to 50 % of the principal pulse amplitude. The appearance of the voltage pre-pulse on the diode leads to the development of explosive emission on the cathode and plasma fill of the anode-cathode gap prior to the electron beam formation. At the formation of the voltage working pulse at the diode the electron beam contraction takes place what causes the DFL arc discharge formation. At that, a higher degree erosion of thin anode foil material takes place. The erosion leads to the foil destruction and consequently decreases the accelerator operation resource. In order to decrease the pre-pulse amplitude at the use of matching (auto)transformer the forced demagnetization of ferromagnetic core has been applied at the beginning of the cycle of the voltage accelerating pulse formation [3-5]

2. Pulsed High-current Electron Accelerator

The accelerator forms the electron beam with the pulse energy of 150…200 J, electron kinetic energy of 450…500 keV and pulse duration at the half-height of 60 ns. Fig. 1 shows the accelerator drawing.

Gas- filled generator of pulsed voltage (GPV) -1 was constructed according to the scheme of Arkadiev-Marx and contains seven cascades of the capacitors K75-74 (40 kV, 47 nF) – two in each cascade. The discharger of the first cascade is made with a trigatron ignition. The self-inductance of GPV is 2.4 μH, impact capacity is 13.4 nF. DFL-2 based on the deionized water has electrical length of 30 ns, the capacity of each line is 6.5 nF, DFL impedance is ~10 Ohm. The total capacity of DFL does not significantly differ from the GPV impact capacity. This provides the optimal conditions of energy transfer from GVP to DFL.

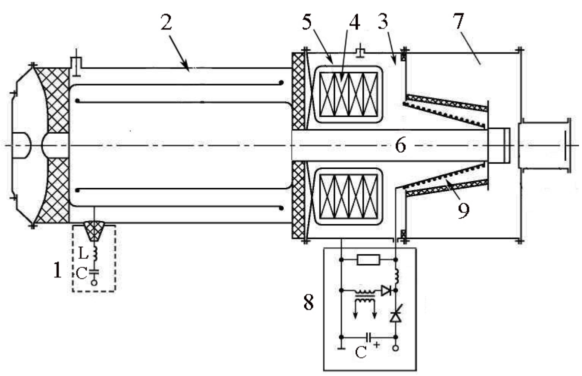

Fig. 1. Accelerator drawing: 1) Arkadiev-Marx generator of pulsed voltage, 2) DFL, 3) oil-filled chamber, 4) matching (auto)transformer, 5) demagnetization coils, 6) cathode holder, 7) diode chamber, 8) demagnetization unit, 9) protective inductance

In the chamber 3 filled with oil the matching (auto) transformer – 4 is placed. The autotransformer contains four circular cores K360×150×25 made of permalloy band 50НП×0.01. Twelve singular coils – 5 are placed around the cores (in the cross-section of magnetic circuit). These twelve coils are uniformly unsoldered from one side to the inner forming line. The other end of the coils – 5 is electrically connected to the chamber body – 3. There is an additional coil which is connected to the transformer coils in the anode-cathode gap. This additional gap is formed by the anode holder – 6, chamber bodies – 3 and diode chamber - 7 of the accelerator.

Thus, the diode is appeared connected along the autotransformer scheme with the twice-time voltage increase relative to DFL voltage output. The use of such a transformer scheme provides four-time increase of the output resistance of nanosecond generator (DFL+transformer) in regard to the DFL impedance. The core sectioning into four rings allows decreasing the voltage on an inter-coil isolation in the core (MgO applied by the cataphoresis method), and provides the duty cycle of 0.72…0.80 for the bands with 10μm thickness. The experimentally measured losses at the demagnetization of permalloy band 50НП×0.01 with the inductance scale of 2.5 Tesla for 100 ns time are within the range of 2…3 mJ/cm^3 and the volume of ferromagnetic core of 6 dm3 are 12…18 J.

Fig. 2 shows oscillograms of voltage formed by GVP U_{GVP} and voltage at the nanosecond generator load U_D.

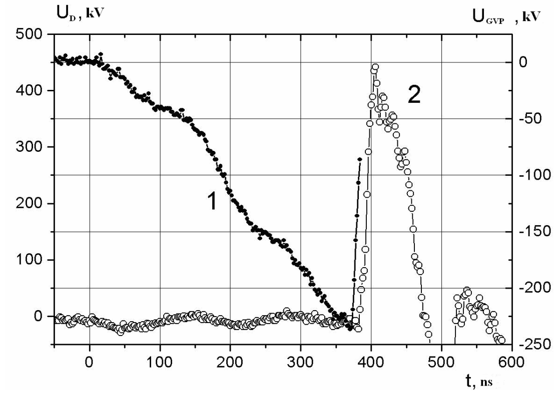

Fig. 2. Voltage oscillograms formed by 1) GVP, 2) nanosecond generator

The amplitude of pre-pulse formed during DFL charge (time interval 0…380 ns in Fig. 2) is determined by the initial magnetic condition of the core transformer. The saturated condition of the transformer is determined by the current formed by the demagnetization unit -8. The current goes along the circuit: protective inductance – 9, cathode holder – 6 and coils – 5 at the capacitor discharge in the demagnetization unit. The energy value stored in the capacitor is ~7 J. Fig. 3 shows the pre-pulse amplitude dependence on the demagnetization current value.

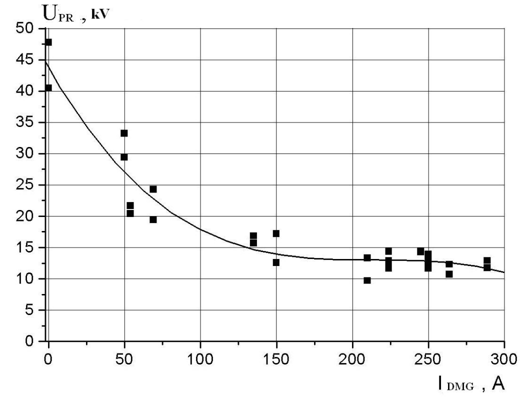

Fig. 3. The dependence of pre-pulse amplitude U_{PR} formed by the nanosecond generator from the demagnetization current I_{DMG}

The inductance of demagnetization coils parallel-connected at the transformer core saturation is ~0.05 μH and significantly less than the GVP inductance (2.4 μH). That is why the voltage inductance fall on the transformer coils with the saturated core is small and the voltage pre-pulse amplitude on the diode does not exceed 2…3 % from the amplitude of the principal voltage pulse. Thus, the pre-pulse does not lead to the explosive emission plasma occurrence in the diode gap.

The developed nanosecond generator provides the stable operation in the mode of electron current generation. The researches of the accelerator operation stability were done at the frequency of 5 Hz during 1.5 minute. The oscillograms of voltage formed by GVP and nanosecond generator were read from the oscillogram Tetronix TDS5035 on a videotape. Then, the maximal voltage of each oscillogram was measured and tabulated. Fig. 4 shows voltage histograms formed by GVP and voltages in the diode which have the amplitude: U_{GVP}=(240±1.2%) kV and U_D=(455±5.3%) kV.

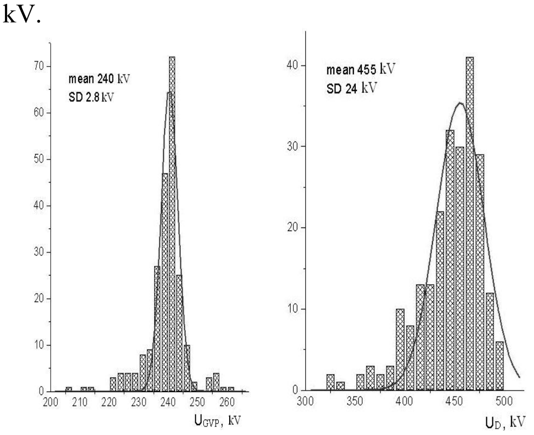

Fig. 4. Histograms of voltage formed by the generator of pulsed voltage U_{GVP} and voltage in the diode U_D. The frequency is 5 Hz. Histogram approximation is done according to the Gauss law

In order to analyze the effectiveness of energy transfer the energy values per pulse in different units of the electron accelerator are given in the table 1. Here NSG1 corresponds to the total output of nanosecond generator energy, and NSG2 corresponds to the output energy of nanosecond generator during the main pulse. As it can be seen from the table 1 the use of transformer allowed to significantly increase the effectiveness of operation of nanosecond generator and the accelerator as a whole.

At the matching of explosive emission diode and a forming line by the transformer with forced magnetization 90…95 % of energy supplied to the diode releases during the main pulse.

Table 1. Energy Distribution per Pulse in the Units of. Electron Accelerator, J

Accelerator	GIV	DFL	NSG1	NSG 2	Electron beam
Without transformer	380 ±10	290 ±10	90 ±5	58 ±5	15±2
With transformer	380 ±10	290 ±10	60 ±5	250 ±5	180±5

In case of forced magnetization lack not more than 65 % of energy stored in DFL is spent for the formation of the main pulse. The further energy loss reduction and accelerator efficiency increase (relation of GVP energy storage to the energy of electron beam per pulse) is possible at the use of forming line discharger with the outside trigger. This will reduce the energy loss due to the discharger response not at a maximal voltage. The application of the matching transformer allowed working with the cathode 60 mm in diameter and anode cathode gap 15…18 mm length without the formation of explosive emission plasma by a voltage pre-pulse with the pressure of 0.1…0.01 Pa.

The application of the forced demagnetization of ferromagnetic core allowed increasing the durability of anode foil, decreasing the negative influence of pre-pulse and providing an output higher than 104 pulses of electron beam through an aluminum foil with the 130 μm thickness. The foil was placed on a support mesh. The developed pulsed electron accelerator was used for researches on plasmachemical synthesis of nanodispersed oxides [6, 7], halogenide conversion, methane hydrolysis [11].

3. High-current Pulsed Ion accelerator

High-current ion accelerator consists of an ion diode and the nanosecond voltage generator with the matching transformer described above. The ion diode with circular anode and external radial magnetic field created by two concentric windings was used [12]. There is no device for a preliminary plasma generation in the diode. The monitoring of parameters of ion diode operation was performed by the measurements of charging voltage of DFL, pulsed voltage on the output of nanosecond generator and total diode current. In order to measure ion current densities, ion energy by the method of measurement of transit time of the stated distance and the measurement of the moment of ion start from the anode the collimated Faraday cylinders with magnetic cutoff of electrons were used. The cylinders were placed at 5-to-30-cm distance from the anode section. In order to measure the total energy and density of ion beam current two copper calorimeters were used. The first one had a central hole. The energy of ion beam gone through the hole of the first calorimeter was measured by the second calorimeter.

Figure 5 shows the scheme of diode unit of ion accelerator.

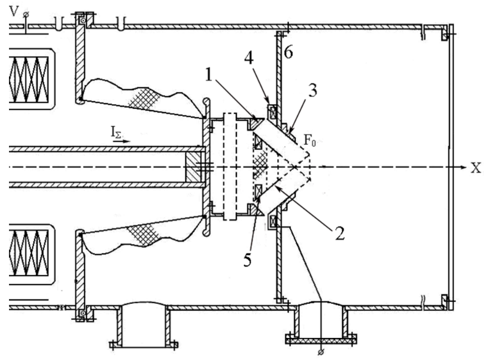

Fig. 5. Functional Diagram of Diode Accelerator Unit: 1) anode; 2) internal and 3) external cone-shaped cathodes; 4) external and 5) internal frames; 6) cathode disk

The ion diode contains a circular anode 1 and two circular cone-shaped cathodes 2 and 3. The anode is connected to the high-voltage output of the accelerator through a divider which operates on a sliding discharge. The anode is made of aluminum or copper (material with high conductivity), the external radius of the ring R_1 is 75 mm, the internal radius R_2 is 55 mm. The working surface of the anode has circular grooves flied with a dielectric (polyethylene or epoxide compound).

The cathodes are placed at the dielectric frames (4 and 5) inside which the electric windings are positioned. The external winding is connected in series to the internal winding and by a different output is connected to the pulsed power source. The cathode system is fixed on a disk 6 together with petitioners. The internal cathode 2 is centered relative to the external cathode by three studs. In one of the studs a conductor for the internal winding power supply is placed. The cathodes are made of steel 1X18H9T 0.8 mm in thickness. Relatively to the working anode surface the edges of external and internal cathodes are placed at 4.2±0.1 mm and 6.5±0.1 mm distance.

Fig. 6 shows the geometry of the anode-cathode gap of the ion diode.

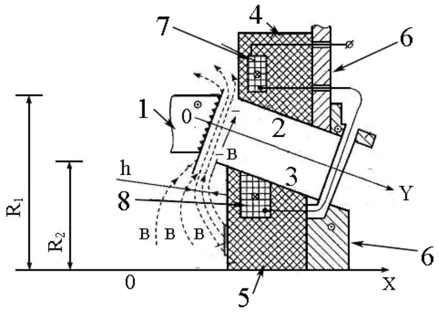

Fig. 6. Ion Diode Construction: 1-6) the same as in Fig. 5; 7) external and 8) internal windings

The distribution of the magnetic field should be done in such a way that the surfaces of equal potential of magnetic field for magnetized electrons coincide to the equipotential surfaces of electric field at the ion acceleration in the diode. The shape of the magnetic field lines in the anode-cathode gap is determined by the geometry of windings 7 and 8 (Fig. 6) and conductivity currents induced in the conductive material of the anode and metal parts of the cathode unit. The magnetic field of the required configuration in the diode gap can be obtained under the condition that the vectorial magnetic potential of windings is equal at the axis 0X. This can be reached when the number of coils W and radii of winding coils centers R are related as $W_1 \cdot R_1 = W_2 \cdot R_2$. The flanges of the cathode disk 6 screen the magnetic flux in the area of ion beam transportation and improve the conditions of compensation of ion volumetric charge by slow electrons.

Prior to the formation of the working pulse in the ion diode the saturated state of the matching transformer core is established by the current pulse of the demagnetization unit. Simultaneously, the voltage pulse is supplied to the windings 7 and 8. Having reached the maximal value of magnetic field in the diode gap the nanosecond generator of pulsed voltage is activated. It forms a working pulse of voltage at the anode. An explosive emission of electrons takes places at the voltage pulse edge from the sharp edges of the cathodes 2 and 3.

Electric field E near the cathode edges has orthogonal component $E^{\perp}$ to the field lines of magnetic field and parallel component $E\|$. At that the latter is directed to the axis 0Y from the edge of both cathodes. For the voltage ~300 kV, the gap d~5 mm an average voltage $E^{\perp}$ is 60 kV/mm and at the inductance B~0.8 Tesla, an average drift motion speed is $7 \cdot 10^7$ m/s. Electrons in the drift motion for the time of plasma formation ($t_0 \ldots t_2$, Fig. 7) can perform almost two complete turnovers by the anode surface around axis 0X. The propagation path of electron motion in the anode-cathode gap represents a trochoid. The height *h* of the trochoid of electron drift motion directed along the axis 0Y to the anode surface is ~1.06 mm. The trochoid height is in proportion to $E^{\perp}$ and depends on the longitudinal component of the electric field $E\|$. The longitudinal component influenced the electrons by the cathode edges imparts a radial electron drift to the axis 0Y and initial deviation of direction of electron motion relatively to the field line vectors of magnetic field. That is why the value *h* can vary from zero value up to ~4.5 mm.

Till the moment t_2 the ion current does not appear. The voltage in the diode increases in the idling mode. When the voltage of electric field reaches some threshold value the electrons drifting along the field lines of magnetic field start reaching the anode surface by the trachoid peaks and form plasma from dielectric and anode metal. At that the electrons reach the anode surface having the maximal speed.

The volumetric charge density in the rotating “electron disk” is determined by the anode potential and is ρ=0.1 Coulomb/m^3. The volumetric charge decreases the voltage of the electric field in the area of electron drift and enforces it before the anode in order to form the ion diode with small anode-cathode gap and high potential. This provides high densities of ion current.

Indirectly, the trochoid height *h* of electron drift motion can be estimated by the trace left on the surface of the internal dielectric frame 5 the width of which is ~3.5 mm. Approximating the radial size of this trace by the field lines of magnetic field *h* can be estimated as 0.5…0.7 mm. This corresponds to the voltage of electric field ~20…30 kV/mm in the area occupied by the drift electrons. The electrons falling to the frame surface 5 have the energy of <30 keV and their charge flow down along the surface to the cathode 2. Note that the explosive emission goes mainly from the cathode edge 2 which has a reliable current circuit through the disk 6 and the smallest gap. The drift motion of ion beam appeared in the traces of ion streams on the cathode surface which has screw structure with coarse pitch.

Typical diagrams of nanosecond generator voltage, total accelerator current and ion current in the diode gap in the matching mode in connection to the voltage in time are shown in Fig. 7. The total diode current consists of ion beam currents and loss currents. Loss currents are a current of electron emission from the cathode edges 1 and 2, residual gas ionization, current of electron emission from flanges 8 and 9. The part of ion beam current is 60 % from the total accelerator current. For the geometry shown in Fig. 6 the magnetic field of ~0.8 Tesla was required which was provided by the capacitor bank with the capacity of 20 μF at the 6 kV voltage. At the magnetic field value in the anode-cathode gap less than 0.64 Tesla the accelerator operated in the mode close to the short-circuit and the diode impedance during the pulse sharply decreased. In the winding space 7 and 8 free from the conductive surfaces the magnetic field not more than 0,4 Tesla was provided.

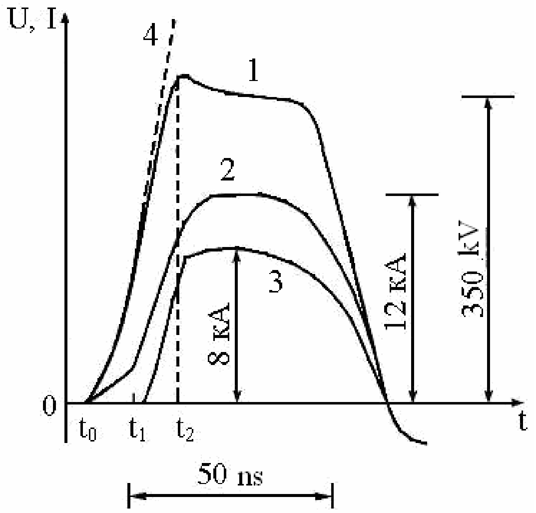

Fig. 7. Diagrams in the matching mode: 1) of voltages at the output of nanosecond generator, 2)of total accelerator current, 3) of ion current, 4) voltage of idling mode. Magnetic inductance in the gap is 0.8 Tesla

The application of magnetic flux compression by the inducted current in the sub-surface anode layer doubled the field in the gap by the anode surface. The ion diode operated satisfactorily if the residual pressure did not exceed $1.5 \cdot 10^{-6}$ Pa.

At the charging voltage of DFL of 165 kV the energy stored in the forming lines was ~180 J. The energy per pulse formed by the nanosecond generator (composition integral of voltage and total current in the generator load) was 150 J. The ion beam at that had the energy of 80±5 J per pulse. In a flat variant the current density in the circular cylindrical beam was ~100 a/cm^2. The anode area was 80 cm^2. In the cone-shaped variant using the ballistic focusing in the spot focus F_0, Fig. 5, with ~40 mm diameter the ion current density of ~600 A/cm^2 was obtained at the density of ion beam energy ~11 J/cm^2. This current density was enough to obtain an ablation plasma and film deposition to the substrate of different materials. For this the spread material was placed in the focus F_0 and the substrate was fixed at the butt-end of the cathode disk 6.

The developed constructions of the ion diode and nanosecond generator with autotransformer at the optimal value of magnetic field 0.8 Tesla provided the matching of impedance of forming lines and impedance of ion diode. The energy of forming lines was extracted in the first pulse (efficiency is higher 95 %), and parasitic oscillations did not appear. This determined the resource of ion diode operation of more than 10^3 pulses. The application of ballistic focusing in the concurrent ion beam allowed obtaining the ion current density in the focus up to 600 A/cm^2 at the diode efficiency ~60 %, at the potential at the anode ~330 kV and voltage pulse duration at half-height 60 ns.

4. Conclusion

The construction of nanosecond generator with matching autotransformer and forced demagnetization of the core prior to the voltage pulse formation was developed. The construction provided the optimal conditions for electron diode operation with planar explosive emission cathode and circular ion diode. The load performance of nanosecond generator allowed forming the pulsed electron and ion beams with high efficiency at the change of geometric diode sizes.

Basing on the developed generator the source of nanosecond electron beams with the kinetic electron energy of 450…500 keV, mean current 6 kA, pulse duration at the half-height 60 ns. The generator was also used for the formation of pulsed ion beam with the ion current density ~600 A/cm^2, energy density ~11 J/cm^2, potential at the anode 300…350 kV.

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