TOMSK POLYTECHNIC UNIVERSITY

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PLASMA-BEAM MATERIALS TREATMENT TECHNOLOGIES

Textbook. Laboratory session

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The book describes the scientific basis of generation, diagnostics and application of pulsed beams of charged particles gigavatt power. Modern methods of monitoring the parameters of charged particles - thermal imaging diagnostics of pulsed electron and ion beams, the acoustic diagnostics are present. Gave specific examples of practical application of high-power beams of charged particles in various technologies.

Designed for students enrolled in the direction 140400 "Power and Electrical Engineering." Specialization - "Engineering and Physics of High Voltage"

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Rreviewer associate professor of applied physics and medical depatment of Omsk State University V.S. Kovivchak

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INTRODUCTION

Cours of laboratory routine is a complement of the course of lectures "Beam-plasma material processing technologies." The course includes 12 separate laboratory work of 2-4 hours each of classroom training and general load-tion 36 hours. The focus is on practical oc-military principles of pulsed beams of charged particles gigavatt power on testbeds. On the research of the pulse electron beam (accelerator TEU-500 [1]), and pulsed ion beams (accelerator Tel TEMP-4M [2]), students perform research of the energy balance of the accelerator, the diode impedance, the stability of the accelerator parameters when operating in the frequency mode, transport and focusing ion beams.

Much attention in the course of the laboratory work on the practical development of modern methods of monitoring the parameters of charged particle beams - thermal imaging diagnostics of pulsed electron and ion beams, the diagnosis of TOF, ion beam acoustic diagnostics. The final part of the course of laboratory work includes specific examples of practical application of high-power beams of charged particles in a variety of technologies:

- Nanostructured surface of metal articles made by pulsed ion beam;
- Development of multi-component thin-film coatings for the spray target pulsed ion beam;
- Formation of radiation color centers in the action of a pulsed electron beam.

In carrying out laboratory work, students master the modern computer programs for processing of the experimental data (Qrigin 8.1 and SmartView™), methods of statistical analysis.

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[1] Remnev G.E., Furman E.G., Pushkarev A.I., Kondratiev N.A., Goncharov D.V. High-current pulsed accelerator with matched transformer: construction and exploitation characteristics. // IEEJ Transactions on fundamentals and materials. – 2004. – Vol. 124. – №6. – P. 491– 495.

[2] Alexander I. Pushkarev, Yulia I. Isakova A gigawatt power pulsed ion beam generator for industrial application // Surface and Coatings Technology (2012) DOI: http://dx.doi.org/10.1016/j.surfcoat.2012.05.094

LABORATORY WORK 1. THERMAL IMAGING DIAGNOSTICS OF ION BEAM

Thermal imaging diagnostics of the total energy of a pulsed ion beam and energy density distribution over the cross section is described. The diagnostics was tested on the TEMP-4M accelerator in the conditions of formation of two pulses: (i) the first plasma□forming pulse is negative (300–500 ns, 100–150 kV) and the second generated one is positive (150 ns, 250–300 kV). The beam composition includes carbon ions (85%) and protons, and the power density is 0.2–3 J/cm^2 (for various diodes). The diagnostics was applied in studies of the powerful ion beam, formed by an ion diode with self-isolation (two pulse mode) and external magnetic insulation in the single-pulse mode. The diagnostics was intended to measure the beam energy density in a range of 0.05–5 J/cm^2 in the absence of erosion and ablation processes on the target. When a thermal imager with a 140 × 160□pixel matrix is used, the spatial resolution is 0.9 mm. The measurement time does not exceed 0.1 s.

The purpose of laboratory work - experimental studies of pulse energy density distribution over the cross section of the ion beam and the balance of energy in the diode.

1.1. Setting to work

1.1.1. Getting experimental waveforms of current and voltage

At this stage, work is needed to apply the skills to work with high-speed digital oscilloscope to obtain the experimental waveforms of current and voltage of the generator output voltage pulses. It should do:

• Close the door to the hall of the high-voltage and in the control room.

• Charge voltage pulse generator.

• Start the TEMP-4M accelerator.

• Get the complete experimental waveforms of the diode current and an accelerating voltage of diagnostic equipment accelerator.

• Save waveforms to USB.

• Process the waveform program Qrigin 8.1.

1.1.2. Measurements of the energy density of the ion beam cross section.

At this stage, work is needed to apply the skills to work with a thermal imaging camera to obtain experimental thermogram IIP. It should do:

• Close the door to the hall of the high-voltage and in the control room.
• Record the initial thermogram target on the imager Fluke TiR10
• Charge voltage pulse generator.
• Start the TEMP-4M accelerator.
• Write a thermogram.
• Process the thermogram program SmartView ™.
• As the temperature distribution at the target calculates concentration distribution of the energy density of the ion beam cross section using Qrigin 8.1.

1.1.3. The study of energy balance diode unit.

The purpose of this section is to obtain experimental dependence PIB energy from the energy supplied to the diode to generate an ion beam. It should do:

1. Close the door to the hall of the high-voltage and in the control room.
2. Record the initial thermogram on the imager Fluke TiR10.
3. Charge voltage pulse generator.
4. Start the TEMP-4M accelerator.
5. Record thermogram on the imager Fluke TiR10.
6. Get the experimental waveforms of electron beam current and voltage with the diagnostic equipment of the accelerator.
7. Record waveform to USB.
8. Repeat steps 2-7 ten times.
9. From the oscillograms of voltage and current to calculate the total energy coming into the diode junction.
10. Process the waveform on the program Origin 7.5.
11. Process thermogram program SmartView ™.
12. In the temperature distribution in the target to calculate the energy density distribution of the ion beam cross-section by using the Origin 8.1.

13. Calculate the energy of the IPI for 10 different pulses and oscillograms of voltage and current for these pulses to calculate the total energy coming into the diode junction.

14. Plot the energy of the IIP from the energy supplied to the diode in the generation of the ion beam.

1.1.4. Making a report on the work.

The report shall be made on the computer and submitted in hard copy format and in Word. It should contain the following sections.

• Experimental waveforms of current and voltage of the generator output voltage pulses (one pulse)

• thermograms PIB on the target (for a single pulse).

• The distribution of the energy density of the ion beam cross section (for a single pulse).

• The energy of the PIB of the energy supplied to the diode in the generation of the ion beam.

• Average efficiency diode unit and standart deviation.

• Discussion of results and comparison with theory.

1.2. Test questions.

1. What parameters of the target is determined by the threshold sensitivity of termovision diagnosis?
2. What physical processes determine the maximum energy density of the PIB, which can be detected with a thermal imaging diagnostics?
3. What is different from the thermal imaging diagnostics of PIB technique using total absorption calorimeter?
4. What determines the spatial resolution of thermal imaging diagnostics?
5. How to calculate the total energy of the PIB on the thermogram?
6. What parameters thermal diagnostics depend on the thickness of the target?

LABORATORY WORK 2. TIME-OF-FLY DIAGNOSTICS OF THE COMPOSITION AND ENERGY SPECTRUM OF ION BEAM

The purpose of laboratory work - study of the composition and the energy spectrum of high-power ion beams.

2.1. Setting to work

2.1.1. Getting experimental waveforms of current and voltage

At this stage, work is needed to apply the skills to work with high-speed digital oscilloscope to obtain the experimental waveforms of current and voltage of the generator output voltage pulses. It should do:

• Close the door to the hall of the high-voltage and in the control room.
• Charge voltage pulse generator.
• Start the TEMP-4M accelerator.
• Get the complete experimental waveforms of the diode current and an accelerating voltage of diagnostic equipment accelerator.
• Save waveforms to USB.
• Process the waveform program Qrigin 8.1.

2.1.2. The measurement of the ion beam formed by a flat-stripe diode with magnetic self-isolation.

At this stage requires applying skills on program Qrigin 7.5, to determine the composition of the ion beam. It should do:

1. Process the waveform program Qrigin 8.1.
2. Construct a waveform of the accelerating voltage and ion current density.
3. According to the relations:

$$\Delta t = D\sqrt{\frac{m_i}{2zU}}. \quad J_{ион} = \frac{4\alpha\,\varepsilon_0\sqrt{2z}}{9\sqrt{m_i}}\frac{U^{3/2}}{(d_0 - vt)^2},$$

to calculate the current density of protons, singly and doubly ionized ions of carbon for the experimentally measured waveforms of the accelerating voltage.

4. Choose the most appropriate computational oscillograms for the experimentally measured waveforms of ion current density.

5. To pick up the gain density ion current for each type of ion.

6. Perform steps 1 - 4 for all five pulses of registered during operation of the accelerator

2.1.3. The study of the energy spectrum of the ions.

The purpose of this section is to obtain experimental data on the energy spectrum of each type of ion. It should do:

1. For each value of the accelerating voltage, the oscilloscope recorded (step 0.4 ns), the ratio:

$$\Delta t = D\sqrt{\frac{m_i}{2zU}}.$$

to calculate the time delay and plot the variation of the kinetic energy of the protons, synchronous with the oscillograms signal of Faraday cup.

2. Divide the entire range of variation of the kinetic energy of the ions into 10 pieces.

3. For each range of variation of the kinetic energy of the ions to calculate the charge density of protons by integration with respect waveform ion current density in the appropriate time interval.

4. Plot the fluence of protons with energies corresponding to the selected portion of the average energy of this part.

5. Repeat steps 1 - 4 for singly and doubly ionized carbon ions.

2.1.4. Making a report on the work.

The report shall be made on the computer and submitted in hard copy format and in Word. It should contain the following sections.

• Experimental waveform accelerating voltage and the ion current density at the output of the generator voltage pulses

• A table with the composition of the IIP and the gain for each component of the PIB.

• The energy spectrum for each component of the PIB.

• Discussion of results and comparison with theory.

2.2. Test questions.

1. What determines the time delay in the arrival of the ion at Faraday cup?

2. How to calculate the density of the ion current waveform at the output of Faraday cup?

3. What ions come earlier in Faraday cup?

4. How to calculate the value of the ion fluence from the charge density?

5. What parameters Faraday cup depend on the diameter of the collimating hole?

6. What parameters affect the depth of the ion path in the matter?

7. Why do I need to use a magnetic or electric cut-off electron for density measurements of the ion current?

LABORATORY WORK 3. POWERFUL ION BEAM ACOUSTIC DIAGNOSTICS

This charter presents the acoustic diagnostics of a pulse ion beam at gigawatt power. Diagnostics testing is conducted using a TEMP-4M accelerator (150 ns, 250-300 kV). The beam is composed of C^+ ions (85%) and protons, the beam energy density is 0.5–5 J/cm^2. A calibration dependence of the piezoelectric tranducer (piezosensor) signal amplitude on the ion beam energy density is observed with the help of the thermal imaging diagnostics. It is shown that the acoustic diagnostics allows measuring the beam energy density in the range of 0.1–2 J/cm^2. The piezosensor signal amplitude stabilization comes with the energy density over 2 J/cm^2 due to the target surface layer melting. Developed acoustic diagnostics were used to conduct a statistical analysis of pulsed ion beams generation, formed by a self-insulated ion diode. It is observed that two independent methods (acoustic and thermal imaging) give close values of a standard deviation in a pulse train. The type of the ion beam energy density dependence on a full charge in the diode (total current integral) corresponds to correlation of the piezosensor signal amplitude and a full charge in the diode. Calibration testing of a diagnostic stand is conducted by a weight-drop method. Also, the dependence of the pressure in the zone of the ion beam absorption on the energy density is determined. It is observed that the proportional factor is equal to 200 (MPa·cm^2)/J in the area of the pressure linear dependence on the energy density. The comparison of observed data with the simulation results is accomplished. Developed acoustic diagnostics do not need in complex equipment and can be used for operation monitoring of pulse ion beam parameters with a repetition frequency to 10^3 pulses/sec.

The purpose of the lab - the study of acoustic diagnostics and calibration parameters of pulsed ion beam formed by the TEMP-4M accelerator.

3.1. Setting to work

3.1.1. Getting experimental waveforms of current and voltage

At this stage, work is needed to apply the skills to work with high-speed digital oscilloscope to obtain the experimental waveforms of current and voltage of the generator output voltage pulses. It should do:

• Close the door to the hall of the high-voltage and in the control room.

• Charge voltage pulse generator.

• Start the TEMP-4M accelerator.

• Get the complete experimental waveforms of the diode current and an accelerating voltage of diagnostic equipment accelerator.

• Save waveforms to USB.

• Process the waveform program Qrigin 8.1.

3.1.2. Calibration of acoustic diagnostics.

At this stage, work is needed to apply the skills to work with a thermal imaging camera to obtain experimental thermogram IIP. It should do:

1. Close the door to the hall of the high-voltage and in the control room.
2. Record the initial thermogram on the imager Fluke TiR10
3. Charge voltage pulse generator.
4. Start the TEMP-4M accelerator.
5. Record thermogram on the imager Fluke TiR10.
6. Record waveform signal from the piezoelectric sensor to USB.
7. Repeat steps 2 - 6 15 times at different duration of the first pulse of the accelerating voltage.
8. Process thermogram program SmartView ™.
9. On the temperature distribution at the target calculates the distribution of the energy density of the ion beam cross section of the.
10. Plot the amplitude of the signal from the piezoelectric sensor of the energy density PIB using Qrigin 8.1.

3.1.3. Making a report on the work.

The report shall be made on the computer and submitted in hard copy format and in Word. It should contain the following sections.

• Experimental waveforms of current and voltage of the generator output voltage pulses

• thermogram IIP on target (only one pulse).

• the energy density distribution of the ion beam to the target cross section (for a single pulse).

• The amplitude of the signal from the piezoelectric transducer of the energy density of the PIB.

• Discussion of results and comparison with theory.

3.2. Test questions.

1. What parameters defined threshold sensitivity acoustic diagnostic?
2. What physical processes determine the maximum energy density of the ion beam, which can be detected by acoustic diagnostics?
3. What is different acoustic diagnostics of the PIB thermography of the energy density of the IIP?
4. What determines the spatial resolution of the acoustic diagnostics?
5. What is direct and inverse acoustic effect?
6. Why the acoustic signal has a sine wave with an amplitude growing?

LABORATORY WORK 4. THERMAL IMAGING DIAGNOSTICS OF HIGH-CURRENT ELECTRON BEAMS

The thermal imaging diagnostics of measuring pulsed electron beam energy density is presented. It provides control of the electron energy spectrum and a measure of the density distribution of the electron beam cross section, the spatial distribution of electrons with energies in the selected range, and the total energy of the electron beam. The diagnostics is based on the thermal imager registration of the imaging electron beam thermal print in a material with low bulk density and low thermal conductivity. Testing of the thermal imaging diagnostics has been conducted on a pulsed electron accelerator TEU-500. The energy of the electrons was 300–500 keV, the density of the electron current was 0.1–0.4 кA/cm^2, the duration of the pulse (at half-height) was 60 ns, and the energy in the pulse was up to 100 J. To register the thermal print, a thermal imager Fluke-Ti10 was used. Testing showed that the sensitivity of a typical thermal imager provides the registration of a pulsed electron beam heat pattern within one pulse with energy density over 0.1 J/cm^2 (or with current density over 10 A/cm^{2,} pulse duration of 60 ns and electron energy of 400 keV) with the spatial resolution of 0.9–1 mm. In contrast to the method of using radiosensitive (dosimetric) materials, thermal imaging diagnostics does not require either expensive consumables or plenty of processing time.

The purpose of laboratory work - studying thermal diagnostic basic parameters of an electron beam: the energy density distribution over the cross section; the electron energy spectrum, the distribution of the absorbed dose in condensed materials.

4.1. Setting to work

4.1.1. Experimental measurements of voltage and current waveforms.

At this stage, work is needed to apply the skills to work with high-speed digital oscilloscope to obtain experimental waveforms of current and voltage of the generator output voltage nanosecond pulses. It should do:

• Close the door to the hall of the high-voltage and in the control room.

• Charge voltage pulse generator.

• Start the accelerator TEU-500.

• Get the experimental waveforms of current and voltage with the diagnostic equipment accelerator.

• Save waveforms to USB.

• Process the waveform on the program Origin 8.1.

4.1.2. Experimental measurements of the energy density distribution of the electron beam cross section.

1. Close the door to the hall of the high-voltage and in the control room.
2. Record the initial thermogram on the imager Fluke TiR10.
3. Charge voltage pulse generator.
4. Run the accelerator TEU-500.
5. Record thermogram on the imager Fluke TiR10.
6. Process thermogram program SmartView ™.
7. According to the initial thermogram calculate the average temperature of the target before firing.
8. On the temperature distribution at the target after the shot to calculate the distribution of the absorbed dose. The heat capacity of polystyrene 1.26 J / (g • deg).
9. Repeat steps 1-8 with the target thickness of 1, 2 and 3 cm
10. Construct the distribution of the absorbed dose in the horizontal section for each target.

4.1.3. Experimental studies of the absorption of the electron beam in the Styrofoam.

1. Close the door to the hall of the high-voltage and in the control room.
2. Charge voltage pulse generator.
3. Run the accelerator TEU-500.
4. Record thermogram on the imager Fluke TiR10.
5. Record experimental waveforms of current and voltage of the accelerator with the diagnostic equipment to USB.
6. Process the waveform on the program Origin 7.5.
7. Process thermogram program SmartView ™.
8. On the temperature distribution at the target to calculate the distribution of the absorbed dose at the depth of the target.
9. Repeat steps 1-8 for other accelerating voltage.
10. Construct the distribution of the absorbed dose at the depth of the target for each mode of operation of the electron accelerator.

4.1.4. Making a report on the work.

The report shall be made on the computer and submitted in hard copy format and in Word. It should contain the following sections.

• Experimental waveforms of current and voltage (only one pulse)

• thermogram of the electron beam on the target thicknesses.

• distribution of the absorbed dose of electron beam cross-sectional thicknesses of targets.

• distribution of the absorption dose of the electron beam at the target depth in the different sections.

4.2. Test questions

1. What methods are used to determine the energy spectrum of electrons?
2. Why to measure the absorbed dose of the electron beam is used styrofoam?
3. What are the parameters of pulsed electron beam affect the absorbed dose?
4. How to determine the change in the spectrum of the electrons in the beam cross section?
5. What determines the spatial resolution of thermal imaging diagnostics of the electron beam?
6. Can I use this diagnosis for control of parameters of the continuous electron beam?
7. What are the parameters of the target to set the minimum and maximum absorbed dose, registrable with a thermal imaging diagnostics?

LABORATORY WORK 5. THE ENERGY TRANFER IN THE TEMP-4M PULSED ION BEAM ACCELERATOR

The results of a study of the energy transfer in the TEMP-4M pulsed ion beam accelerator are presented. The energy transfer efficiency in the Blumlein and a self-magnetically insulated ion diode was analysed. Optimization of the design of the accelerator allows for 85 % of energy transferred from Blumlein to the diode (including after-pulses), which indicates that the energy loss in Blumlein and spark gaps is insignificant and not exceed 10-12%. Most losses occur in the diode. The efficiency of energy supplied to the diode to the energy of accelerated ions is 8-9% for a planar strip self-magnetic MID, 12-15% for focusing diode and 20 % for a spiral self-magnetic MID.

The purpose of the lab - the study of diagnostic equipment and experimental studies of the energy balance in the high-power ion beam generator TEMP-4M.

5.1. Setting to work

5.1.1. Experimental measurements of voltage and current waveforms.

At this stage, work is needed to apply the skills to work with high-speed digital oscilloscope to obtain experimental waveforms of current and voltage of the generator output voltage pulses of the Marx generator and Blumlein. It should do:

1. Close the door to the hall of the high-voltage and in the control room.
2. Charge voltage pulse generator.
3. Start the TEMP-4M accelerator.
4. Get the experimental waveforms of current and voltage with the diagnostic equipment accelerator.
5. Record waveform to USB.
6. Record thermogram on the imager Fluke TiR10.
7. Process the waveform on the program Origin 8.1.
8. From the oscillograms of voltage and current to calculate the total energy coming into the Blumlein.
9. From the oscillograms of voltage and current to calculate the total energy coming into the diode junction.
10. Process thermogram program SmartView ™.

11. In the temperature distribution in the target to calculate the total energy of the ion beam.

12. Repeat steps 2-11 ten times.

13. Plot the power supplied to the diode junction and the energy of the ion beam on the energy supplied to the Blumlein.

5.1.2. Making a report on the work.

The report shall be made on the computer and submitted in hard copy format and in Word. It should contain the following sections:

• Experimental waveforms of current and voltage at the output of the Marx generator and Blumlein (only one pulse)

• thermogram IIP on target for this pulse.

• The dependence of the energy supplied to the diode junction and the energy of the ion beams on the energy supplied to the Blumlein DFL.

• Average efficiency diode unit and the standard deviation.

• Analysis of the results and conclusion.

5.2. Test questions

1. What types of energy losses occur in the double forming lines when the accelerator is working in single pulse mode?

2. What types of energy losses occur in the double forming lines when the accelerator is working in double-pulse mode?

3. How to calculate the energy stored in the double forming line?

4. How to calculate the energy loss in the arrester?

5. Can I make a non-inductive resistive loads connected to the output of the generator of high-voltage nanosecond pulse?

6. How to calculate the energy supplied to the diode junction when operating the accelerator on a resistive load?

7. What types of energy losses occur in the diode unit?

8. Why do I need to provide impedance matching energy with a characteristic impedance of the double forming line?

9. How does the parasitic inductance of the load on the efficiency of the ion beam?

LABORATORY WORK 6. LOSSES IN A PULSED ELECTRON BEAM DURING ITS FORMATION AND EXTRACTION FROM THE DIODE CHAMBER OF AN ACCELERATOR

The results of experimental studies of the current and charge balance in the diode unit of the TEU-500 high-current pulsed electron accelerator (an accelerating voltage of 350--500 keV, a half-height pulse duration of 60 ns, and a total kinetic electron energy of 250 J/pulse) during generation of an electron beam are presented. Planar diodes with multipointed cathodes having diameters of 43--60 mm and manufactured from graphite, copper, and carbon felt were studied. It is shown that the electron-beam divergence in the anode--cathode gap caused by a distortion in the electric field at the periphery of the cathode is the main source of parasitic losses in planar diodes. The half-angle of divergence is 68º at small anode--cathode gaps and decreases to 60º with an increase in the gap. When the diode impedance is matched to the generator's output impedance (at a gap of 10--12 mm), the charge loss is within 12%.

The purpose of the lab - the study of diagnostic equipment and experimental investigations of the balance of energy in the diode unit generator TEU-500.

6.1. Setting to work

6.1.1. Experimental measurements of voltage and current waveforms.

At this stage, work is needed to apply the skills to work with high-speed digital oscilloscope to obtain experimental waveforms of current and voltage of the generator output voltage nanosecond pulses. It should do:

- Close the door to the hall of the high-voltage and in the control room.
- Charge voltage pulse generator.
- Start the accelerator TEU-500.
- Get the experimental waveforms of current and voltage with the diagnostic equipment accelerator.
- Save waveforms to USB.
- Process the waveform on the program Origin 8.1.

6.1.2. The calculation of the energy balance

• from the waveform of current and voltage to calculate the total energy coming into the diode junction of the accelerator.

• from the waveform of current and voltage to calculate the energy of the electron beam

• from the waveform of current and voltage to calculate the change of energy in reactive elements diode unit.

• Perform a statistical analysis of the data.

6.1.3. Making a report on the work.

The report shall be made on the computer and submitted in hard copy format and in Word. It should contain the following sections:

• Experimental waveforms of current and voltage at the output and the DFL (only one pulse)

• The dynamics of change in the energy of the accelerator diode unit (only one pulse)

• Average efficiency diode unit and the standard deviation.

• Analysis of the data and conclusions

6.2. Test questions

1. What describes the product of the accelerating voltage to the total current flowing in the diode unit?
2. How to calculate the efficiency of the diode unit?
3. How to calculate the total energy of the electron beam?
4. What processes in the diode limit the full current?
5. At that consumes energy supplied to the diode assembly of the accelerator?
6. How to measure the accelerating voltage, the total current and current of the electron beam?

LABORATORY WORK 7. RESEARCH ON THE PLASMA DYNAMICS IN A MAGNETICALLY SELF-INSULATED ION DIODE WITH EXPLOSIVE EMISSION POTENTIAL ELECTRODE

The results of an experimental investigation of the plasma dynamics in a magnetically insulated ion diode in bipolar-pulse mode are presented. The experiments were done at the pulsed TEMP-4M accelerator by formation of a first negative pulse (100 ns, 150–200 kV) and a second positive pulse (80 ns, 250–300 kV). The voltage-current diode characteristics were used to analyze the plasma behavior in the anode-cathode gap. It is shown that, during the first pulse, a discrete emissive surface is formed on the graphite potential electrode and a plasma forms by explosive-emission, which before the second pulse comes, fills the whole working surface of the electrode and spreads to the anode-cathode gap. An analytical expression is obtained for the total current in the cellular structure approximation. It is shown that the current build-up for a cathode surface with discrete emitting centers is described satisfactorily by a modified Child-Langmuir formula with a form factor decreasing from $F = 6$ to 1. It is found that, once plasma formation at the graphite potential electrode is complete and until the second positive pulse, the plasma speed is constant and equals 1.3 ± 0.2 cm/μs.

The purpose of laboratory work - experimental studies of the dynamics of explosive plasma ion diode with magnetic self-isolation.

7.1. Setting to work

7.1.1. Experimental measurements of voltage and current waveforms.

At this stage, work is needed to apply the skills to work with high-speed digital oscilloscope to obtain experimental waveforms of current and voltage of the generator output voltage pulses of the Marx generator and Blumlein. It should do:

1. Close the door to the hall of the high-voltage and in the control room.
2. Charge voltage pulse generator.
3. Start the TEMP-4M accelerator.
4. Get the experimental waveforms of current and voltage with the diagnostic equipment accelerator.
5. Record waveform to USB.

7.1.2. The calculation of the diode impedance in the double-pulse mode.

At this stage it is necessary to perform the analysis of the experimental values of the impedance of the diode modeling impedance (with and without the effect of the plasma compression) and to compare the calculated and experimental values. It should do:

1. Process the waveform on the program Origin 8.1.
2. Calculate the experimental values of the diode impedance.
3. Run simulation diode impedance on the relations:

$$R_{calc} = \frac{U}{S_0 \cdot J_e} = \frac{(d_0 - v \cdot t)^2}{S_0 \cdot 2.33 \cdot 10^{-6} \cdot U^{1/2}}$$

$$R_{calc} = \frac{[d_0 - v(t - t_0)]^2}{S_0 \cdot 2.33 \cdot 10^{-6} \cdot 1.86 \cdot U^{1/2}}$$

4. Repeat steps 1 - 3 for the different pulses.

7.1.3. The calculation of the rate of expansion of explosive plasma from the experimental waveforms of current and accelerating voltage.

1. Process the waveform on the program Origin 8.1.
2. Perform the calculation of explosive expansion rate of the plasma ratio:

$$v(t) = \frac{1}{t}\left[d_0 - \sqrt{\frac{2.33 \cdot 10^{-6} \cdot S_0 \cdot U^{3/2}}{I_e}} \right],$$

7.1.4. Making a report on the work.

The report shall be made on the computer and submitted in hard copy format and in Word. It should contain the following sections:

• Experimental waveforms of current and voltage (only one pulse);

• Calculated and experimental dependence of the impedance of the diode at different duration of the first pulse;

• The experimental dependence of the change rate of the explosive plasma for generating the PIB:

• Analysis of the results and conclusions.

7.2. Test questions

1. How does the area of the anode and the cathode-anode value influence on the diode impedance?

2. Why ion diode impedance described mainly electronic component of the total current of the diode?

3. What physical processes lead to a change in the effective anode-cathode gap diode when operating in the double-pulse mode?

4. What methods are used to measure the rate of expansion of the plasma?

5. What modes are characteristic for a diode with an explosive emission cathode?

6. What physical processes cause the effect of the plasma compression?

LABORATORY WORK 8. STATISTICAL ANALYSIS OF THE ION BEAM GENERATION IN A SELF MAGTICALY INSULATED DIODE

The paper presents the results of a study on shot to shot variation in energy density of an ion beam formed by a diode with self-magnetic insulation and explosive emission opcathode. The experiments were carried out with the TEMP-4M accelerator gerating in double-pulse mode: the first pulse is of negative polarity (300-500 ns, 100-150 kV), and this is followed by a second pulse of positive polarity (150 ns, 250-300 kV). It was found that the standard deviation of the energy density does not exceed 11 %, whilst the variation in ion current density was about 20-30 %. The ion current density only weakly depends on the accelerating voltage and the other output parameters of the accelerator with the coefficient of determination $R < 0.3$. At the same time, the correlation between the energy density of the beam and output parameters of the accelerator is strong with $R > 0.9$. These results can be explained by the presence of charge exchange neutral atoms which are produced thought charge exchange process between beam ions and molecules in a neutral layer near the anode. With the energy of neutrals of 5-10 keV, the fluence can reach up to $(2\text{-}4)\cdot 10^{15}$ cm^{-2} per pulse. The ability to produce large-pulsed fluxes of energetic neutrals may have unique applications of its own. Self-magnetically insulated diodes utilizing an explosive-emission cathode have an operational lifetime of up to 10^7 shots, since there is negligible degradation of the electrode surface, which make it promising for various technological applications.

The purpose of laboratory work - experimental studies and statistical analysis of the stability of the generator pulse ion beams TEMP-4M.

8.1. Setting to work

8.1.1. Experimental measurements of voltage and current waveforms.

At this stage, work is needed to apply the skills to work with high-speed digital oscilloscope to obtain experimental waveforms of current and voltage of the generator output voltage pulses of the Marx generator and Blumlein. It should do:

1. Close the door to the hall of the high-voltage and in the control room.

2. Charge voltage pulse generator.

3. Start the TEMP-4M accelerator.

4. Get the experimental waveforms of current and voltage with the diagnostic equipment accelerator.

5. Record waveform to USB.

8.1.2. Register waveforms in a series of pulses.

At this stage it is necessary to register the 50-60 oscillograms of voltage and current at the output of GIN and output during operation of the accelerator DFL TEMP-4M in the frequency mode. It should do:

1. Start the TEMP-4M accelerator in the frequency mode at start of GZI-6 on the pulse repetition rate of 1 pulse for 10 seconds.

2. To take a picture of each pulse waveforms from the oscilloscope screen four signals. Run the item for 50-60 pulses.

8.1.3. Statistical analysis of the stability of the accelerator.

1. Photos with the registration of the following options:
- the breakdown voltage of the preliminary spark gap;
- the breakdown voltage of the main spark gap;
- the duration of the first pulse;
- the amplitude of the accelerating voltage pulse;
- the amplitude of the pulse current in the diode unit;
- the pulse amplitude of the ion current density.

2. To process the data on the program Origin 8.1. Calculate for each parameter mean and standard deviation.

8.1.4. Making a report on the work.

The report shall be made on the computer and submitted in hard copy format and in Word. It should contain the following sections:

- current and voltage waveforms (for a pulse);
- histogram of the distribution for each parameter;
- table with the average value of each parameter and the standard deviation in absolute and relative terms.

8.2. Test questions

1. What is the standard deviation?

2. What are the parameters of the accelerator affect the stability of ion beam?

3. How to calculate the standard deviation of the energy density of the PIB for known values of the standard deviation of the ion fluence and the accelerating voltage?

4. What determines the correlation coefficient?

5. What parameters characterize the stability of the physical quantity?

6. Under what conditions is the stability of the energy density of the ion beam can be higher than the stability of the ion current density?

7. What devices detect the ion current density and energy density of the PIB?

LABORATORY WORK 9. TRANSPORTATION AND FOCUS OF THE POWER ION BEAM

This article presents the results of a study on transferring a pulse ion beam at gigawatt power. This beam is formed by a self-magnetically insulated diode with an explosive-emission cathode. Research is conducted using a TEMP-4M accelerator in a double-pulse forming mode, the first (plasma-forming) is negative (300–500 ns, 100–150 kV), and the second (generating) is positive (150 ns, 250–300 kV). To increase the effectiveness of ion beam focusing, a metal shield is installed on a grounded electrode. Investigations are performed into a strip focusing diode, a cone diode and a spiral diode with metal shields of different constructions. It is observed that for a strip focusing diode, a pulse ion beam with a width half its height decreases from 60 mm (of a diode without shield) to 40–42 mm, and the ion energy density in the focus increases by 1.5–2 times and amounts to 4–5 J/cm^2. Analyses of different mechanisms of ion deviation from the initial path are performed: Coulomb repulsion with charge neutralisation disbalance, influence of electromagnetic fields, etc. It is shown that the concentration of low-energy electrons exceeds the concentration of ions by 1.3–1.5 times in the ion beam formed by a strip focusing diode. The use of a metal shield improves the shielding of the ion transfer area, prevents the loss of low-energy electrons from a pulse ion beam and breaks down its electrical neutrality.

The purpose of laboratory work - experimental studies of transport and geometric focus high power ion beam formed in the ion diode with magnetic self-isolation.

9.1. Setting to work

9.1.1. Experimental measurements of voltage and current waveforms.

At this stage, work is needed to apply the skills to work with high-speed digital oscilloscope to obtain experimental waveforms of current and voltage of the generator output voltage pulses of the Marx generator and Blumlein. It should do:

1. Close the door to the hall of the high-voltage and in the control room.
2. Charge voltage pulse generator.
3. Start the TEMP-4M accelerator.

4. Get the experimental waveforms of current and voltage with the diagnostic equipment accelerator.

5. Record waveforms to USB.

9.1.2. Measurements of the energy density of the cross section of the PIB

At this stage, work is needed to apply the skills to work with a thermal imaging camera to obtain experimental thermogram IIP. It should do:

1. Close the door to the hall of the high-voltage and in the control room.
2. Charge voltage pulse generator.
3. Start the TEMP-4M accelerator.
4. Get the experimental current waveforms of the electron beam and voltage diagnostic equipment of the accelerator.
5. Record waveform to USB.
6. Record thermogram on the imager Fluke TiR10.
7. Repeat steps 2-6 three times at each distance from the diode to a target.
8. Process thermogram program SmartView ™.
9. On the temperature distribution at the target to calculate the energy density distribution over the cross section of the ion beam using Qrigin 8.1.

9.1.3. The study of energy balance diode unit.

The purpose of this section is to get the energy dependence of IIP power supplied to the diode to generate an ion beam. It should do:

1. From the oscillograms of voltage and current to calculate the total energy coming into the diode junction.
2. In the temperature distribution in the target to calculate the energy density distribution of the ion beam cross-section by using the Origin 7.5.
3. Repeat steps 2-7 ten times.
4. Calculate the energy of the PIB for 10 different pulses and oscillograms of voltage and current for these pulses to calculate the total energy coming into the diode junction.
5. Plot the energy of the PIB from the energy supplied to the diode in the generation of the ion beam.

9.1.4. Making a report on the work.

The report shall be made on the computer and is presented in a printed form. It should contain the following sections:

1. Experimental current and voltage waveforms (for a pulse);
2. Thermogram of the ion beam on the target at a different distance from the diode to the target;
3. Energy density distribution over the cross section PIB at a different distance from the diode to the target;
4. Change in total energy PIB during transport.
5. Analysis of the findings and conclusions.

9.2. Test questions.

1. What processes affect the focus ion beam?
2. What is the divergence of the ion beam?
3. Due to some physical processes improves focusing of ion beams with metal screens?
4. What is a skin-layer?
5. What methods are used to focus the beam of charged particles?
6. Why do I need to provide the charge neutralization of the ion beam?
7. In what ways is provided by charge neutralization of the ion beam?

LABORATORY WORK 10. NANOSTRCTURING METAL SURFACES UNDER THE INFLUENCE OF PULSED ION BEAM

The pulsed character of HIPIB action defines the principal difference between processes taking place in the surface layer under the PIB action and under the conventional ion implantation. The thin near-surface layer (with thickness depending on ion range and thermometric conductivity of metals) absorbs energy transferred by the beam for the pulse duration time. For nanosecond PIB, the depth of this surface layer is ~1–10 mm. As a result of the investigation on HIPIB influence on materials, one can say that practical application of HIPIBs is based on both the heating of surface layers and short-pulse doping. In the first case, the result of the beam influence is similar to the action of pulsed laser radiation, nanosecond electron beams (in particular, low energy electron beams), pulsed plasma and sparks. Depending on the target material, the power density is from 5×10^6 to 10^9 W/cm^2. Thus, the ion energy and current density are chosen according to this requirement. In the second case, both ion implantation and energy influence take place. The action of high power ion beams with power flow density $\leq10^6$–10^7 W/cm^2 leads to simultaneous implantation of the doping atoms and heating of the surface layers with consequent rapid cooling after pulse termination.

10.1. Setting to work

10.1.1. Experimental measurements of voltage and current waveforms.

At this stage, work is needed to apply the skills to work with high-speed digital oscilloscope to obtain experimental waveforms of current and voltage of the generator output voltage pulses of the Marx generator and Blumlein. It should do:

1. Close the door to the hall of the high-voltage and in the control room.
2. Charge voltage pulse generator.
3. Start the TEMP-4M accelerator.
4. Get the experimental waveforms of current and voltage with the diagnostic equipment accelerator.
5. Record waveform to USB.

1. .

10.1.2. MIP processing of the titanium sample

The purpose of this section is to conduct modification of the surface layer of the sample using the ion beam. It should do:

1. Install the samples in a vacuum chamber of the accelerator TEMP-4M.
2. Close the vacuum chamber and pumped to a pressure of 0.1 Pa.
3. Close the door to the hall of the high-voltage and in the control room.
4. Charge voltage pulse generator.
5. Start the TEMP-4M accelerator.
6. Repeat steps 4 and 5 3 times.
7. Turn off the source of the charging voltage, close the valve vacuum system, fill the air in the chamber and a diode to get treated samples.

10.1.3. The study of the surface morphology and hardness of the surface layer of the treated samples.

The purpose of this section - to perform testing of samples after exposure to high power ion beam. It should do:

1. To perform testing of the morphology of the original and the treated surfaces of samples in the optical microscope. Are pictured with ethyl image source and the irradiated sample.
2. To investigate the morphology of the original and the processed sample surfaces at the atomic force microscope. Save the image source and the surface of the irradiated sample.
3. To measure the hardness of the initial sample and the sample after processing PIB.

10.1.4. Making a report on the work.

The report shall be made on the computer and submitted in hard copy format and in Word. It should contain the following sections:

1. Experimental waveforms of current and voltage of the generator output voltage pulses
2. Thermogram IIP on the target.
3. The distribution of the energy density of the ion beam cross section.
4. Images of the surface of the original target and the target ion beam irradiation. Images at different Increasing obtained by optical and atomic force microscopes.

5. Experimental data on the hardness of the target.
6. Findings of the research.

10.1.5. Test questions.

1. What physical processes result in a change morflogii sample surface under the influence of the ion beam?
2. What kinds of treatment are used to change the properties of the surface layer of your products?
3. Advantages and disadvantages of the modified metal products pulsed ion beam.
4. What is the depth of the changes in the properties of metal products pulsed ion beam?

LABORATORY WORK 11. OBTAINING OF BIOACTIVE COATING ON THE STEEL AND TI SUBSTRATES FROM ABLATION PLASMA

The results of investigating calcium-phosphate films deposited from ablation plasma formed by powerful ion beam are presented. The coatings on titanium, steel and ceramics substrates are obtained. The investigations of the composition and structure of the films by methods of Auger, IR and roentgen-fluorescent spectroscopy are performed. It was shown that the coatings keep stoichiometric composition of the sputtered target. Medical-biological examinations prove that the coatings are not toxic. Unlike the films formed by magnetron sputtering, the surface of the obtained calcium-phosphate films has optimal class of roughness for development of bone tissue cell medium.

11.1. Setting to work

11.1.1. Selection of the required energy density of the ion beam

The purpose of this section is to gain hands-on experience with an ion diode with magnetic self-isolation, and learn how to adjust the energy density of the MIP on the target by changing the distance from the diode to the target. At this stage, work is needed to apply the skills to work with a thermal imaging camera to obtain experimental thermogram IIP. It should do:

- Close the door to the hall of the high-voltage and in the control room;
- Charge voltage pulse generator;
- Start the TEMP-4M accelerator;
- Write a thermogram on the imager Fluke TiR10;
- Process the thermogram program SmartView ™;
- As the temperature distribution at the target to calculate the energy density distribution over the cross section of the ion beam using Qrigin 7.5.

11.1.2. Preparation of thin-film coatings.

It should do:

1. Cut a strip of Mylar substrate required size, wipe it with alcohol.
2. Fix the target and the substrate according to the scheme of the reduced below 118 with all distances.

3. Pump-down cycle of the working chamber to a residual pressure of 2 • 10-4 Pa using a vacuum position of the accelerator.

4. Close the door to the hall of the high-voltage and in the control room.

5. Charge the capacitance-voltage pulse generator accelerator.

6. Start the ion accelerator, making the required number of pulses.

7. Close the valve. Carefully remove the backing from the deposited film.

11.1.3. Determination of the elemental composition of the deposited film.

To determine the elemental composition of the film should perform the following steps:

1. To analyze the elemental composition of the film X-but-fluorenstsentnogo review in the Scientific-Analytical Center of TPU.

2. Process the data on the composition of the film for different samples and bring to the table

11.1.4. Making a report on the work.

The report shall be made on the computer and submitted in hard copy format and in Word. It should contain the following sections:

1. Energy density distribution over the cross section IIP.
2. Steam distribution of film thickness on the substrate.
3. Data on the elemental composition of the deposited film.
4. The conclusions from the results of experiments.

11.2. Test Questions

1. List the major advantages and disadvantages of pulsed laser deposition.
2. What physical processes form the basis of the deposition of plasma exploding wires?
3. What is the difference between exposure to laser radiation and electron beam on the substance of the ion?
4. What are the advantages of pulsed ion deposition before the pulsed laser deposition?
5. What are the main components is pulsed ion accelerator?
6. What requirements must meet the sputtering target?
7. How is the film deposition by pulsed ion deposition?

LABORATORY WORK 12. FORMATION OF COLOR CENTERS IN RADIATION EXPOSURE PULSED ELECTRON BEAM

12.1 Introduction

The purpose of laboratory work - study the formation of radiation-induced color centers in optical materials under the influence of pulsed electron and ion beams.

12.1. Setting to work

12.1.1. Selection of the required energy density of the ion beam

The purpose of this section is to gain hands-on experience with an ion diode with magnetic self-isolation, and learn how to adjust the energy density of the MIP on the target by changing the distance from the diode to the target. At this stage, work is needed to apply the skills to work with a thermal imaging camera to obtain experimental thermogram IIP. It should do:

• Close the door to the hall of the high-voltage and in the control room;

• Charge voltage pulse generator;

• Start the TEMP-4M accelerator;

• Write a thermogram on the imager Fluke TiR10;

• Process the thermogram program SmartView ™;

• As the temperature distribution at the target to calculate the energy density distribution over the cross section of the ion beam using Qrigin 7.5.

12.1.2. The formation of color centers in radiative glass samples.

1. Set stack of three panes diode output node accelerator.
2. Close the door to the hall of the high-voltage and in the control room.
3. Charge voltage pulse generator.
4. Run the accelerator TEU-500.
5. Get the experimental waveforms of current and voltage with the diagnostic equipment accelerator.
6. Record waveform to USB.
7. Repeat steps 1-6 ten times.

12.1.3. The measurement of the absorption spectrum of the irradiated glasses.

1. A measurement of the absorption spectrum of non-irradiated glass sample and each of the three samples irradiated at AvaSpec Avantes Fiber Optic Spectrometer System AvaSpec-1024.

2. Record the absorption spectra to USB.
3. Process the absorption spectra of the program Origin 7.5.

12.1.4. Making a report on the work.

The report shall be made on the computer and submitted in hard copy format and in Word. It should contain the following sections.

- Experimental waveforms of current and voltage (only one pulse)
- distribution of the absorbed dose of electron beam cross-section.
- The absorption spectra of non-irradiated and irradiated glasses.
- Conclusions of the work.