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VOLTAGE SOURCE UP TO 30 kV WITH PULSATION NOT MORE THAN 0.1%

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A DC source with a voltage of 30 kV with a ripple of less than 0.1% has been developed and manufactured for accelerating and focusing electrons in a dielectric laser accelerator on a chip structure. The source, which has a smooth voltage change limit from 10 to 30 kV, with a ripple of 0.1% over the entire voltage range in the specified range, is made on the basis of a 3-phase network. Such voltage stability is necessary for the correct recording of the energy of electrons accelerated by a laser pulse.

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INTRODUCTION

Research in the field of new methods of charged particle acceleration is a topical and important area of modern physics. To carry out such studies, it is necessary to ensure high accuracy and stability of the voltage source, since this is a critically important parameter that affects the energy spectrum of accelerated particles. At present, we plan to conduct experiments on electron acceleration in dielectric laser accelerators (DLA) using various chip structures [1]. To carry out these experiments, it is necessary to create a voltage source that has the ability to smoothly adjust the output voltage in the range from 10 to 30 kV with a ripple factor of no more than K_R=0.1%. It is important to note that the source must be constant, both in voltage and current. These parameters will make it possible to isolate the increase in energy ΔE in accelerated electrons and to analyze the energy spectrum of electrons. A highly stable source with limiting parameters is necessary for accelerating electrons on a periodic dielectric structure using laser radiation from a terawatt femtosecond laser developed at the NSC KIPT [2]. The requirement for the magnitude of the initial electron energy pulsation is smaller due to the fact that the expected acceleration rate is about ΔE=200 eV [3], which is confirmed by the experimental results presented in [4].

Creating a voltage source with such high requirements is a complex task that requires the use of new technologies and scientific developments. It is important to develop new approaches to the design of voltage sources that provide high accuracy and stability of the output voltage, as well as reduce the level of ripple. Traditional two half-wave rectifiers of industrial frequency without a filter on a load with a resistance R other than zero demonstrate a voltage ripple of about 11% [5]. Improved voltage rectification circuits from two independent sources provide a lower ripple value, not exceeding 1% [6]. However, the specified value of the ripple does not meet the specified specifications (specifications). When designing a power supply at an increased frequency (no more than 30 kHz), technological problems arise due to the need to eliminate parasitic capacitances and inductances. To solve this problem, an improved voltage source was created, providing a ripple not higher than K_R = 0.1%.

1. ELECTRICAL CIRCUIT FOR POWER SUPPLY FOR ACCELERATION AND FOCUSING OF THE ELECTRON BEAM

As noted above, high-voltage single-phase power frequency transformers are used with subsequent rectification or voltage multiplication. Filtering such a voltage is difficult, since it is necessary to have high-capacity capacitors for high voltage, and the use of chokes in load is not rational due to the small amount of current. It is possible to make the power supply at an increased frequency (no more than 30 kHz), but, as noted above, technological problems arise. According to the specifications, the rectifier must provide a smooth change in voltage over a wide range without changing the magnitude of the ripple, which is a rather difficult task for high-frequency converters.

To manufacture a power source for accelerating and focusing an electron beam that meets the conditions of technical specifications, a three-phase rectification circuit with a neutral wire is proposed. It should be noted that at the same rectified voltage U_H, the phase voltage in the bridge rectifier circuit is approximately 2 times less than in a three-phase rectification circuit with a neutral wire. The proposed rectifier circuit shown in Fig. 1.

The difficulty of using an industrial three-phase network lies in the fact that in different phases, consumers independent of each other load the phases with different loads, which is reflected in the magnitude of the voltages, and voltage drops in different phases are unpredictable. In this case, voltage stabilizers must be additionally included in each phase. In the scheme of Fig. 1 voltage regulators are not shown; instead, autotransformers are included in each phase. The circuit works as follows: the START button turns on the starter; voltage is applied to the inputs of the autotransformers.

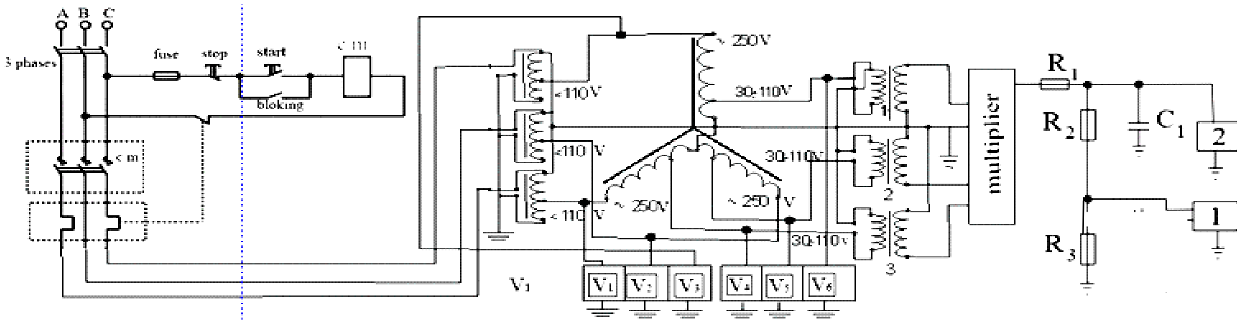

Fig. 1. The circuit diagram of the block is straightened: 1 – three-phase vibrator; 2 – load; 3 – oscilloscope; R1 and C1 – RC filter; R2, R3, R4, and C2 ripple meter circuit parameters

At the output of each autotransformer, according to the readings of voltmeters V_1, Y_2, V_3 (see Fig. 1), the voltage U=110 V is set. This voltage is applied to the 250 V sockets of the three-phase autotransformer. This improves the accuracy of setting the applied voltage to the load of the rectifier. It is controlled (in order to avoid phase imbalance) by the second three voltmeters V_4, V_5, V_6. To the inputs of NOMs.

(industrial high-voltage transformers) an adjustable (from 0 to 110 V) three-phase voltage is supplied from the autotransformer, while the maximum voltage at the output of each is 10 kV. The outputs of these transformers are connected in a star and connected to the inputs of a three-phase high-voltage rectifier (1) Fig. 2. The rectifier output includes a kilo voltmeter for U=30 kV (see not shown in Fig. 1), an additional resistance $R1=61{\cdot}10^6\ \Omega$, a smoothing capacitance C1=0.25 μF.

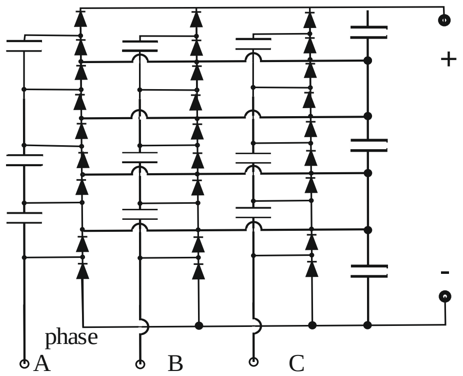

Fig. 2. Three phase rectifiers, three phase rectifiers: diode type HVM12, the same type capacitors K15-10, 31.5 kV, 4700 pF

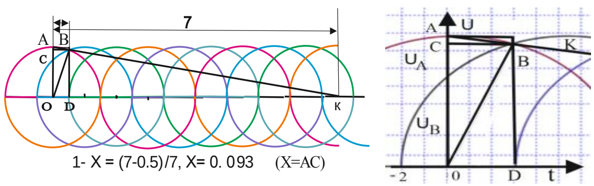

Fig. 3. To the calculation of the pulsation coefficient. B is the point of intersection of two phases

Fig. 3 shows the sinusoids of a three-phase voltage. To determine the pulsation coefficient K_R, we find the intersection point of two sinusoids, for example, U_A voltage on phase A and U_B voltage on phase B (see Fig. 2), solving the equation:

$$U_A \sin(\omega t - 2\pi/3) = U_B \sin(\omega t), \qquad (1)$$

we get OD=0.5.

Triangles ΔAKO and ΔBKD are similar. Solving the equation AO/OK=(AO-AC)/(OK-OD), we get AC=0.093 ($K_{R,}$ got the ripple coefficient in the ideal circuit. Note that this value is equal in the case of $U_A=U_B$). It should be noted that such a value of the ripple coefficient is possible with a sinusoidal voltage of a three-phase network. However, in practice deviations are observed due to non-uniform load, both ohm and inductive, largely spontaneously. In the literature [7, 8], values from 0.67 to 0.057 are given for pulsations. The latter meaning is explained as follows. Taking into account the fact that currents flow in both directions in the phases of the secondary winding of the transformer during the period, the ripple coefficient of the rectified current is small.

The filter circuit is shown in Fig. 1. $X_c \ll R_n$; $X_c \ll R_1$, choose $R_1=0.2\ R_n$, where R_1 is the filter resistance, R_n is the load resistance. X_c is the capacitance of the capacitor.

An indicator of the quality of the smoothing filter [5] is the smoothing coefficient q, $q=K_{R\cdot out}/K_{R\cdot in}$, where

$$q = K_{Rout} K_{Rin} m \omega C_1 (K_{Rout} + K_{Rin}), \qquad (2)$$

where m=3 (three-phase network), ω is the cyclic frequency. C_1 is the capacitance of the capacitor.

For reliable measurement of the AC voltage applied to the oscilloscope, select the scale of the scale of the oscilloscope n_1 (n_1=0.01 volts per division): $U_1/U_2=3{\cdot}10^{-3}$ V. To measure the DC component – U_2=30 V, which on the scale of the oscilloscope (n_2=10 V per division), respectively, from the ratio $U_1=U_2\ R_2/R_3$, then $U_1/U_2=R_2/R_3=10^3$, $R_2=R_3{\cdot}10^3\ \Omega$. R_2 we give the value $R_2 - 61{\cdot}10^6\ \Omega$ (resistance power R_2 W_2=15VA), and we get $R_3=61{\cdot}10^3\ \Omega$.

According to the specifications, the ripple at the filter output ripple factor $K_{Rout}=10^{-3}$. At the output of the multiplier, we take ripple factor $K_{Rin}=10^{-1}$, then $q=K_{Rout}/K_{R.in}=10^{-2}$. From the expression for q (2) we determine the parameters of the filter $R_1C_1=1.45{\cdot}10^{-6}$ we choose R_1 (in the diagram of Fig. 4) equal to $R_1=10^3\ \Omega$, C_1=0.014 μF.

For technical reasons, in the current circuit C_1=0.25 μF. As the main load R_1, we determine the current value $I=U_1/R_1=0.5\cdot10^{-3}$ A, then the power W of the resistance R_1 $W_1=0.25$ mW.

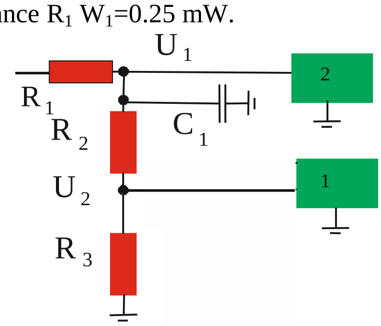

Fig. 4. A fragment for measuring the ripple coefficient is given: 1 – the oscilloscope, 2 – load

The input of the first channel of the oscilloscope 1 (see Fig. 3) determines the variable component from the connection point R_3 and $R_{2.}$ The ratio of these values shows the magnitude of the ripple in the output circuit of the multiplier, as well as at the input to the load, taking into account the division factor.

As practice has shown, the ripple coefficient remained constant within the specified values when the output voltage changed from 10 to 30 kV. The assembled model of the rectifier was tested at a maximum voltage of 30 kV under loading for two hours.

The experimental setup consisted of a high-voltage voltmeter, a divider, and an oscilloscope. The high-voltage voltmeter measured the voltage of the signal, which was then divided by a factor of 1000 using the divider. The divided signal was then measured using the oscilloscope with a 25 ms and 5 µs timebase.

In Fig. 5, the results of experimental pulsation measurements are presented. In Fig. 5,A, the high-voltage voltmeter reading is 21.4 kV. The yellow line in Fig. 5,B and C indicates the channel displaying the DC component after the divider, which has a level of 21.4 V, corresponding to the expected division coefficient of 1000.

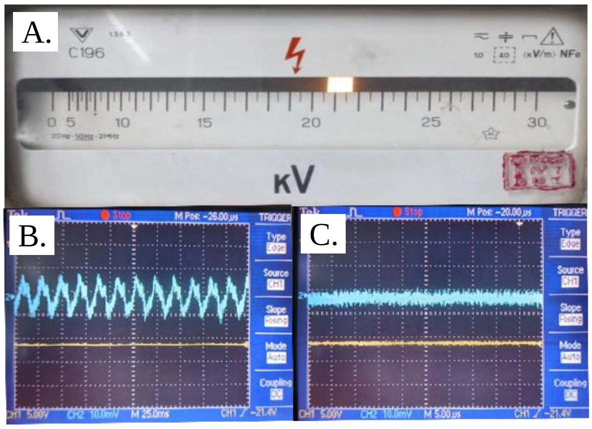

Fig. 5. The results were obtained with various measurements of the characteristics of the power supply according to the 21.4 kV protocol. A – High-voltage voltmeter reading; B – Oscilloscope readings on a 25 ms sweep; C – Oscilloscope readings on a 25 µs sweep

In Fig. 5,B, the blue curve represents the AC component taken from the divider circuit. Pulsations with a frequency of 50 Hz are visible on the oscilloscope, indicating the presence of power supply interference. To reduce the 50 Hz pulsations, methods such as shielding of the power cables were used, which resulted in a pulsation magnitude of 20 mV but did not completely eliminate them.

Low pulsation levels are important for obtaining accurate experimental results, as power line interference can significantly distort the measured values. Conducting measurements with a 5 µs oscilloscope sweep allowed for more precise measurements and more reliable experimental results, disregarding the 50 Hz pulsations. The pulsation level for a 5 µs sweep was reduced to 8 mV.

Since a pulsation level of 8 mV was achieved during the experiment with a 25 µs sweep, this is a good result, especially considering that the oscilloscope initially showed pulsations with a frequency of 50 Hz.

Fig. 6 illustrates the external appearance of the high-voltage power supply system. Fig. 6,A presents a photograph of the control panel consisting of three LATRs, a three-phase transformer and informational voltmeters. On the table, there is a divider and a measuring system consisting of a high-voltage voltmeter and an oscilloscope. Fig. 6,B shows three high-voltage NOM transformers. Finally, in Fig. 6,C, the multiplication circuit immersed in transformer oil is depicted, which is necessary to reduce the risk of high-voltage breakdown.

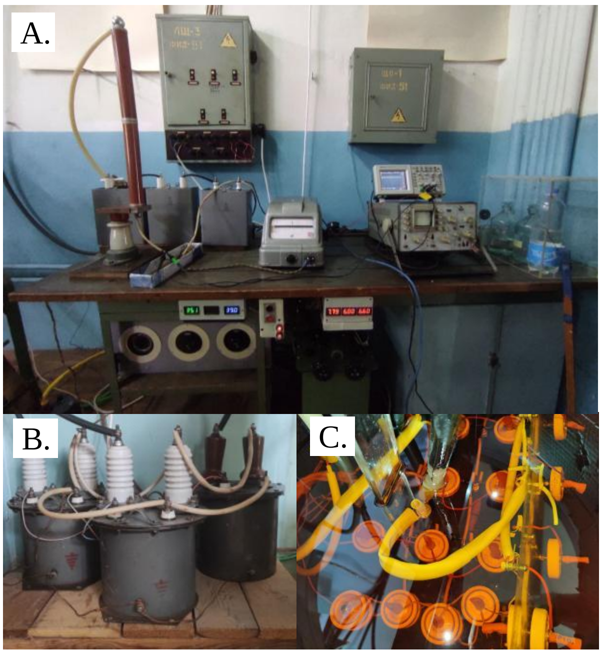

Fig. 6. External view of the high-voltage power supply system. A – Control panel and measuring part with voltage divider. B – High-voltage NOM transformers. C – Oil-immersed multiplier circuit

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REFERENCES

1. A.V. Vasiliev, A.N. Dovbnya, A.M. Yegorov, et al. Works in the NSC KIPT on the creation and application of the CPA laser system // *Problems of Atomic Science and Technology*. 2018, No 4(116), p. 289-293.
2. A.V. Vasyliev, A. Povrozin, G.V. Sotnikov, et al. Influence of the profile of the dielectric structure on the electric fields excited by a laser in dielectric accelerators based on chip *// 12th Int. Particle Acc. Conf. IPAC2021, Brazil, JACoW, TUPAB247,* 2026-2029 p.
3. J. Breuer. *Dielectric laser acceleration of non-relativistic electrons at a photonic structure:* Dissertationat the Faculty of Physicsof the Ludwig Maximilian University Munich, 2013, p. 106.
4. A.V. Vasyliev, A.O. Bolshov, K.V. Galaydych, A.I. Povrozin, G.V. Sotnikov. Acceleration of electron bunches using periodic dielectric structures with and without coating *// Problems of Atomic Science and Technology*. 2021, No 4(134), p. 60-64.
5. M.I. Kuznetsov. *Fundamentals of electrical engineering*. M.: "Proftehvidav", 1960, p. 23.
6. G.A. Krivonosov and I.M. Onishchenko. Dzherela zhivlennya with small pulsation coefficients for the proton injector of the technological priskoryuvach *// Problems of Atomic Science and Technology*. *Series "Plasma Electronics and New Methods of Acceleration" (4)*. 2004, No 4, p. 67-89.
7. R.M. Tereshchuk, K.M. Tereshchuk, S.O. Sedov. Dovidnik of the radioamator // *Napivprovidnikovi priymalni pristroï.* Kiev: "Naukova Dumka", 1962, p. 507 (in Ukrainian).
8. https://i.imgur.com/EpjV8GS
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ДЖЕРЕЛО НАПРУГИ ДО 30 кВ З ПУЛЬСАЦІЄЮ НЕ БІЛЬШЕ 0,1%

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Розроблено та виготовлено джерело постійного струму напругою 30 кВ з пульсаціями менше 0,1% для прискорення та фокусування електронів у діелектричному лазерному прискорювачі на структурі мікросхеми. Джерело, що має плавну межу зміни напруги від 10 до 30 кВ, з пульсаціями 0,1% по всьому діапазону напруг у зазначеному діапазоні, виконано на основі 3-фазної мережі. Така стабільність напруги необхідна для правильної реєстрації енергії електронів, що прискорені лазерним імпульсом.