DESIGN OF HIGH-CURRENT PULSE ELECTRON ACCELERATOR

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INTRODUCTION

For some applications (see, for example, [1]) there are required powerful high-current accelerators with electron beam power of several TW and higher, maximum energy of accelerated electrons of ~2 MeV and bremsstrahlung pulse duration of ≤ 40 ns. For such facilities it is expedient to use a system aimed at forming high-voltage pulses of accelerating voltage with high efficiency. In the accelerators with capacitive method of energy storage most frequently used are single (SFL) or double (DFL) forming lines providing at V_0 charging voltage the formation on a matched load (mode of maximum efficiency) of the voltage pulses (of rectangular shape ideally) with the amplitude $V_0/2$ and V_0, respectively. For a specified above energy of electrons the charging voltage of SFL and DFL should be at a level of 4 and 2 MV, respectively. Besides, to increase reliability of accelerator operation it is desirable to decrease at the unchanged efficiency the charging voltage of the line under whose effect a set of components and units are under charging process within a comparatively long (~1 μs) time period. From the point of view of creating high-power multi-module facilities the insurance of a high time accuracy of accelerator turn-on is an important problem.

In the course of creating high-current linear induction accelerators there has been developed in VNIIEF a new type of multi-cascade high-voltage pulse generators formed of homogeneous transmission lines of a similar electric length [2, 3]. As in such facilities during transfer from one cascade to another the impedance changes stepwise, they are called generators on step lines (SL). The energy stored initially in many cascades concentrates after a switch turn- on and resulting from wave processes at the generator output. For a specific relation of impedances the entire energy transmission to the load is possible with the formation on it of a rectangular-shape pulse. The pulse duration does not depend on the full generator size but is characterized by a double electric length of a separate cascade. At the expense of wave processes there is realized in a set of schemes a significant increase of voltage what gives the opportunity for the application considered to reduce the charge voltage to ~1 MV. Below presented is the description of a project of accelerator with a 2 MeV electron energy and 1 MA current at ~60 ns duration of current pulse (FWHM).

PRINCIPAL CIRCUIT DIAGRAM FOR A PULSE FORMING SYSTEM

Basing on a comparative analysis of different SL-based generators with a capacitive method of energy storage there is chosen for the accelerator a circuit presented in Fig. 1a. It combines two devices: a generator based on a five-cascade double step forming line (DSFL, Fig. 1b) and a two cascade pulse duration converter (Fig. 1c). Let us consider each of the above-mentioned devices separately.

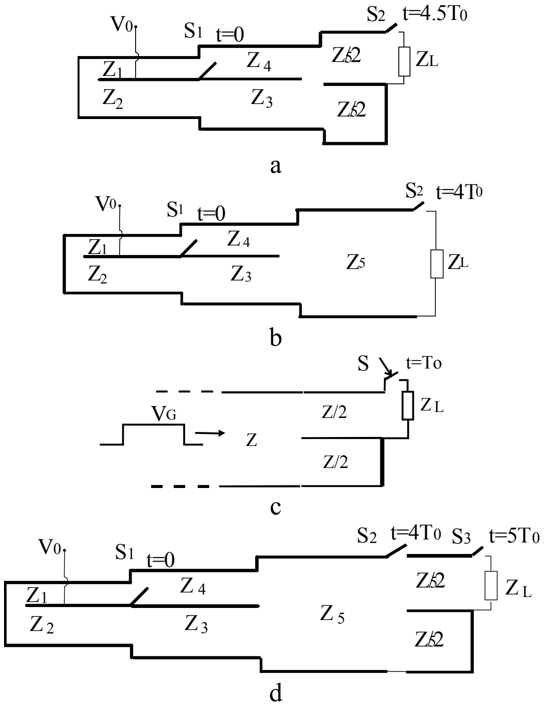


Fig.1. Principal circuit diagrams.

DSFL (Fig. 1b) is formed by 5 homogeneous lines of a similar electric length T_0 and possesses ideally a 100-% efficiency for the following relation of impedances: $Z_2 = 3Z_1$, $Z_3 = 15Z_1/4$, $Z_4 = 5Z_1/4$, $Z_5 = 15Z_1$. At $t = 0$ time moment, when maximum charging voltage V_0 of lines 1÷4 is achieved, S_1 switch is turned on. Z_L load is connected to DSFL output with Z_5 impedance through a pre-pulse switch S_2 at $t = 4T_0$ time moment. On a matched load $Z_L = Z_5 = 15Z_1$ there is formed a voltage pulse of $2T_0$ duration and $3V_0$ amplitude, within which the energy is entirely transmitted to the load. In the idle mode the output voltage exceeds the charging one by a factor of 6. This circuit underwent experimental testing during the creation of electron pulse accelerator STRAUS, two STRAUS-2 accelerators and LIA-10M accelerator injector [4].

A two-cascade converter that is a particular case of a device with arbitrary number of cascades [5] is formed by the connected in series at the input similar lines with $T_0/2$ electric length and $Z/2$ impedance. The output of one of the lines is shorted and to the output of the other one the load is connected through the S

switch. A rectangular voltage pulse of V_G amplitude and $2T_0$ duration is transmitted from the external generator along the transmission line with Z impedance. With the matched load $Z_L = Z/2$, connected through S switch with T_0 delay time as related to the time of the first electromagnetic wave coming from the generator there is formed a rectangular voltage pulse of V_G amplitude and T_0 duration. Ideally, the energy coming from the external generator is entirely transmitted to the load. The experimental testing has shown that the converter provides the increase of power and current by a factor of two (as compared to the generator) due to the double reduction of pulse duration.

Such a converter can be connected to any generator of rectangular pulse including DSFL as it is shown in Fig. 1d. Furthermore, the converter can be connected instead of the DSFL output cascade (Fig. 1a), that makes it possible to decrease the full size of the forming system and to reduce the number of switches. On a matched load there should be formed a rectangular voltage pulse of $3V_0$ amplitude and T_0 duration. The scheme of DSFL offers the possibility of varying within specific limits the relation of impedances at a high efficiency unchanged. For a forming system with 1 MV charging voltage there are selected the following impedances: $Z_2 = Z_3 = 2.8Z_1$, $Z_4 = Z_1$, $Z_5 = 10Z_1$. The output impedance of the generator with a converter constitutes $Z_5/2$. Ideally, on a matched load there should be obtained the voltage of 2.58 MV at the current of 0.89 MA and power of 2.3 TW. The calculated efficiency constitutes 98%. When limiting the maximum voltage on the diode to 2 MV ($Z_L = 3.2Z_1$) the current increases up to 1.1 MA with reduction of the power to 2.2 TW and the efficiency of 93%.

SCHEME OF HIGH-VOLTAGE ACCELERATOR PART

The scheme of the high-voltage accelerator part is presented in Fig. 2. It incorporates the system of high-voltage pulse formation, pre-pulse switch (PS), water transmission line (WTL), unit of sectioned insulator, magnetically insulated transmission line (MITL) and diode with a target unit. The system of high-voltage pulse formation is designed on the basis of DSFL having a ~50 ns electric length of coaxial lines with water insulation. For the purpose of decreasing the accelerator length the lines with Z_4 (0.58 Ohm), Z_1 (0.58 Ohm), Z_2 (1.62 Ohm) and Z_3 (1.62 Ohm) impedances are arranged in series on a radius within the limits of one axial dimension (~ 1.8 m). The electric capacity of DSFL is ~235 nF. To the output of DSFL there is connected a converter consisting of two homogeneous coaxial lines with equal impedance of 2.9 Ohm and similar electric length of ~25 ns. At the converter output there is installed a PS with the help of which the pulse formed is delivered to WTL connecting the output of the forming system and the unit of the sectioned insulator. The total length of the forming system is 2.8 m, its diameter is 2.5 m. The charging of DSFL to the working voltage of 1 MV is supposed to be realized from two connected in parallel Marx generators with the total maximum energy store of 190 kJ (at 100 kV). According to preliminary estimations each generator should include 12 cascades of voltage multiplication using 4 connected in parallel capacitors of 400 nF (for example, of IKM-100-0.4 type) in each cascade. Moreover, the output capacity of two generators is ~270 nF, their operation charging voltage is 90 kV (160 kJ) while the time of DSFL charging is ≤ 800 ns. In the course of charging the maximum electric field strength on the cylindrical surface of high-voltage DSFL electrode does not exceed 110 kV/cm.

The DSFL switching is supposed to be implemented with the aid of 40 gas-filled controlled spark switches of trigatron type arranged symmetrically on azimuth in the DSFL case. The PS should be turned on ~260 ns after the DSFL multi-channel switch operation. To decrease the intrinsic inductance of PS it is supposed to use 6 gas-filled spark trigatron switches similar by design to the pre-pulse switch of STRAUS-2 accelerator, but of the increased size. The control signals will be sent through cable lines positioned in the grounded internal near-axis cavity of DSFL. The unit of PS is separated from the DSFL and WTL volumes by dielectric diaphragms and is filled with transformer oil for the purpose of decreasing the pre-pulse amplitude and increasing the quality of the pulse formed.

The coaxial WTL serves to deliver the pulse from the forming system output to the sectioned insulator unit. Its impedance is matched with the output impedance of the forming system and constitutes 2.9 Ohm at the external diameter line equal to 1.62 m. The length of the line depends on a choice of the scheme of arranging a multi-module facility as a whole, but for the time isolation of PS inductance and accelerating tube it should be not less than 1.5 m.

The sectioned insulator external diameter constitutes ~1.2 m, its length ~ 0.5 m. The insulator dimensions were selected following the condition of the required electric strength provision as well as the condition of minimum permissible distortion of the pulse shape. The average strength of the electric field on the vacuum insulator surface constitutes ~50 kV/cm at the maximum value near 70 kV/cm. The total inductance of the sectioned insulator unit is ~35 nH. The external volume of the sectioned insulator is separated from the transmission line volume by a dielectric diaphragm and is filled with transformer oil.

MITL serves to transmit voltage pulse from the sectioned insulator to the diode with a target unit that is aimed at accelerating the electron flow formed in MITL and at its transforming into a bremsstrahlung pulse. The vacuum impedance of MITL will constitute ~4.3 Ohm. By design it is proposed to make MITL of two sections: conical and cylindrical ones. The diameters of internal and external electrodes of MITL section are approximately equal to 18 cm and 16.8 cm.

The overall dimensions of the accelerator are as follows: length ~8 m, width – 3 m, height – 4 m.

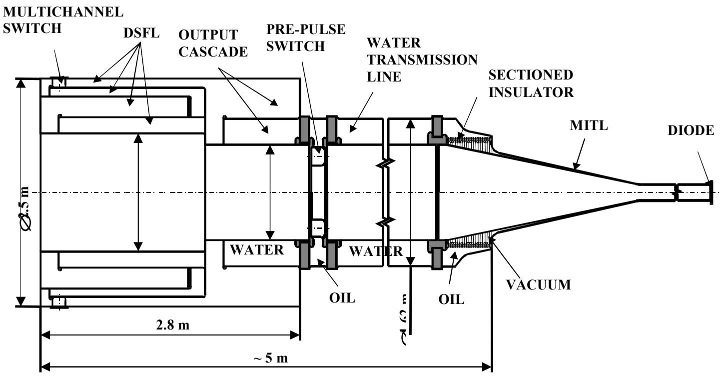
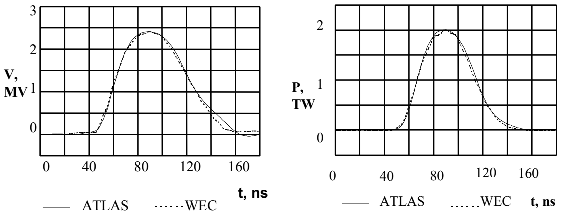


Fig. 2. Scheme of high-voltage accelerator part.

NUMERIC SIMULATION RESULTS

There was performed a lot of calculations to study the process of high-voltage pulse formation, to optimize geometry and parameters of accelerator components as well as to find time-amplitude characteristics of pulses delivered to MITL input. To increase authenticity of the results obtained the calculations were performed using two independent algorithms realized and developed in VNIIEF WEC and ATLAS codes. The electromagnetic code WEC [6] is based on the numerical solution of Maxwell's equations realized using a method of integral equations in two-dimensional geometry. It allows to calculate forming systems of complex configuration with the arbitrary number and geometry of electrodes, with the availability of material media of different conductivity, dielectric and magnetic permeability; it makes it possible to use inhomogeneous space grid for both coordinates. The calculation technique of ATLAS code is based on a one-dimensional model using a method of equivalent circuits. The given method is less exact, but it allows to perform calculations at considerably higher rate (~1000 times). The electromagnetic processes in the lines with distributed parameters were calculated by solving telegraph equations using a method of modified characteristics [7]. Inhomogeneities in the places of DSFL lines junction were described by the shorted transmission line segments with short electric length and reactive elements in accord with the technique presented in [8, 9]. It should be mentioned that ATLAS code was successfully used at the development of powerful LIA-10M and STRAUS-2 facilities, moreover, the experimental results obtained on them coincided - with good accuracy (~10%) - with the calculated data.

The pulses of voltage and power on the MITL input obtained as a result of calculations are presented in Fig. 3a, b. The amplitudes of voltage and power constitute 2.4 MV and 2.0 TW at the duration of pulses (FWHM) being equal to 62 and 47 ns, respectively. Referring to the above figures it will be observed a good coincidence, with the accuracy of ~10%, of calculation data for both codes. Let us mention that the voltage pulse amplitude (~2.4 MV) is by approximately 7% lower than the theoretical value of 2.58 MV corresponding to the idealized model. Nevertheless, the efficiency of energy transmission from the forming system to MITL turns out to be high enough – at a level of ~85%. Moreover, the module efficiency characterized by the relation between the energy of the pulse formed and the energy stored in Marx generators can be as high as ~60%. The pre-pulse voltage at the output of the forming system occurring before the basic pulse arrival, is revealed in the form of a group of short pulses with the duration of less than 20 ns (FWHM) and the amplitude that is not higher than 85 kV.



a b

Fig. 3. Calculation pulses of voltage (a) and power (b) at the MITL input.

The advantages of the considered accelerator are as follows: small size (dimensions of the forming system - ∅ 2.5 × 2.8 m^2), sufficiently high efficiency (~60%), comparatively small number of the switches used (46 units with the exception of Marx generators switches) and low values of pre-pulse amplitude and duration at the forming system output.

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