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HIGH-VOLTAGE MODULATOR FOR ION LINAC INJECTOR WITH SMOOTH PULSE DURATION CONTROL

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The ion linear accelerators stable operation essentially depends on the ion injector. To ensure maximum capture of the ion beam injected into the accelerating structure, the injector must be able to adjust the beam parameters. The paper describes the developed new injector power supply system, built on modern assemblies, which allows smoothly changing the modulator pulse duration in the range of 300…2000 μs. The analysis was carried out and the shortcomings of the previous systems were eliminated. The expected increase in the accelerated ion beam current is 15…20%. Related results include a decrease in the parasitic load capacitances of pulsed devices, a reduction in size, and the rejection of high-voltage isolation transformers, which increases the reliability of the accelerator.

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INTRODUCTION

An increase in the efficiency of a linear accelerator and an increase in its output parameters directly depend on the parameters of the injected ion beam. In most cases, this depends on the emittance of the ion beam formed by the injector. Obtaining the optimal accelerated current for each accelerating structure will also be determined by the possibility of smooth adjustment of the high voltage injector pulse. In our case, the duration of the microwave pulse, which creates an accelerating field in the structure, makes it possible to increase the high-voltage injector pulse duration by a factor of 1.5, thereby providing a larger number of accelerated ions on the target. The solution of this problem requires the development of a new injector power supply system high-voltage modulator. The next section provides a brief analysis of the high-voltage modulator currently used, and considers various options for constructing this node. The modulator included in the power supply system of the injector is made on the basis of a double forming line, as a switch thyristors are used. This modulator provides an output pulse with a duration of 600 μs and an amplitude of 120 kV.

HIGH-VOLTAGE MODULATORS BASIC CONSTRUCTION SCHEMES

A simplified diagram of this switch is shown in Fig. 1.

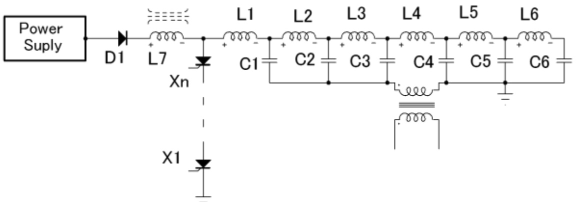

Fig. 1. Simplified scheme of a modulator based on a double forming line

The traditional construction of a modulator for circuits, using a double forming line, shows on Fig. 1. The step-up transformer is a modulator load. The transformer high-voltage (120 kV) pulse output is fed to the injector. The change in the amplitude pulse is provided by changing the supply voltage magnitude. As a switch, 10 class 12 thyristors connected in series are used. This inclusion allows you to increase the voltage switched by thyristors up to 12 kV. Equalization of thyristors potentials is achieved by using connected in series resistors chain. The thyristors start is provided by the simultaneous supply the positive polarity triggering pulses to all control electrodes, by separate transformer winding. The triggering pulse of each thyristor is under the potential of the cathode of the corresponding thyristor and has its own amplification channel. Turning off the thyristor key occurs due to the thyristor current drop to 0. The pulse formed on the load is close to rectangular and has duration $\tau_и = 2\tau_л$ ($\tau_л$ is the delay time of the artificial circuit). Obviously, a change in the output pulse duration of such modulator construction, can be achieved only by double forming delay line parameters changing, namely by changing the values of its constituent elements (capacitance or inductance), or by introducing additional LC links. This method is rather inconvenient since the change in duration is discrete and requires access to high-voltage elements. Besides, additionally connected chains will have rather significant dimensions and must be homogeneous, i.e. have identical denominations to avoid distortion of the modulator output pulse shape. It is this defect of such pulse shaping schemes that leads to the need to use other methods for constructing modulators that provide a smooth change in the duration of the output pulses.

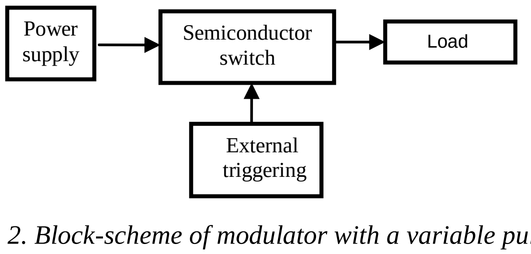

Fig. 2. Block-scheme of modulator with a variable pulse duration at the output

In low-voltage semiconductor technology, the implementation of such devices is widespread and does not cause problems. A simplified block diagram of the shapers is shown in Fig. 2. In such a scheme, the power source is connected to the load through a semiconductor switch for a time determined by the duration of the trigger pulse.

The output pulse amplitude of such a modulator will be determined by the ability of the key to withstand the required voltages, currents and the allowable power dissipated on the key. The successful implementation of a high-voltage modulator based on this principle will be determined only by the parameters of the high-voltage controlled switch.

ELEMENTAL BASEHIGH VOLTAGE CONTROLLED KEY CHOICE

Below, only the semiconductor element base will be considered, since electronic and ion devices require significant heating power and have a large internal resistance. One of the most common devices capable of switching currents of the kilo ampere level are thyristors.

A positive feature for their introduction into high-voltage devices is the well-proven methods of including them in serial chains, which make it possible to increase the value of the switched voltage [1]. The ease of turning on the thyristor is determined only by the need to achieve the required current amplitude of the control electrode. However, turning off the thyristor requires a significant amount of effort. In this case, it is necessary to reduce the thyristor current to the level of the turn-off current and is most often achieved by introducing additional thyristor anode blocking circuits. The presence of series-connected chains complicates the solution of such a problem since it is required to put such chains on each thyristors. Modern bipolar transistors can switch tens amperes currents, and have simple ways to control them, but they have rather low maximum allowable voltages on the electrodes (250 V), which leads to a complication of hardware implementation. One of the most high-voltage devices (up to 6 kV), moreover, capable of switching kilo-ampere currents, are assemblies (modules) produced on the basis of IGBT [2 - 4]. Such modules are manufactured by Semikron [5]. However, the significant cost of the latter, and their limited availability cast doubt on the feasibility of using them as a switch.

Therefore, the use of IGBT as the switch of this modulator comes to the fore. Semiconductor IGBTs are a symbiosis of high-impedance field-effect transistors with a bipolar transistor structure at the output. This allows it to switch large currents, with a small voltage drop across it. The constantly expanding range of IGBT devices, with an increase in the level of currents switched by them (over 50 A), in combination with an increase in the maximum allowable voltage (over 1200 V), add arguments in favor of our choice.

FEATURES OF IGBT OPERATION IN SERIES

The semiconductor switch constructions based on IGBT leads to connect them in series in order to increase the value of the switched voltage up to 10 kV. Such parameters of the key will allow using it in a number of blocks that are necessary for further upgrades of the accelerator.

Let's consider the main connecting circuits for IGBTs in series, which make it possible to avoid the occurrence of overvoltage's. High voltage can be the cause of semiconductors failure in dynamic mode. Three cascade connection options for IGBT surge protection is shown on Fig. 3: using clamping diodes, floating capacitors and varistors.

However, these protection options showed themselves well only in the statistical mode of operation (on or off states) [6]. In this case a small spread in the parameters of the leveling elements are presents. In the dynamic mode, change IGBT switching time and amplitudes of gates control signals at the devices, additional processes are activated. It is also necessary to provide an optimal thermal regime and take measures to equalize IGBT reverse currents, since they significantly affect the processes of turning devices on and off, leading to an avalanche-like increase in power on individual devices in a series chain.

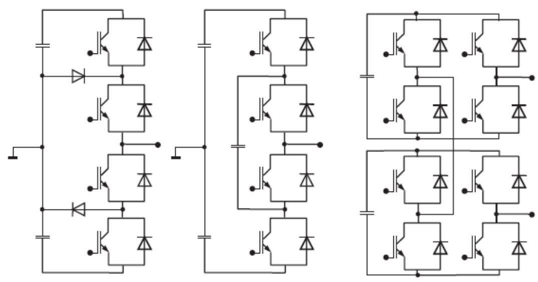

Fig. 3. Methods of options for protecting IGBTs from overvoltage's when they are connected in series in a static mode

In the off state, the distribution of potentials on the IGBT electrodes is determined by the blocking characteristics of the elements connected in parallel. The higher the leakage current and the lower the resistance, the lower the voltage on the corresponding IGBT. When the element is heated, the reverse current grows exponentially, and for different components the temperature coefficient can differ markedly. Thus, even in a statistical state of leakage, with an initially uniform distribution of the voltage drop across the elements, a further redistribution of potentials is possible. The above protection methods of eliminating the consequences of this are aimed. During the serial switch chain operation, dynamic asymmetry may occur (change of operating modes during the switching process).The term dynamic displacement, when chains operate in a pulsed mode, is also often used. The resulting offset leads to a mismatch in switching times for each of the series-connected IGBTs. The transistor that turns off first and turns on last is the one with the most voltage, and accordingly it is loaded earlier than the others. As a result, the temperatures of the keychain junctions turn out to be uneven, increasing the leakage currents and the spread of the turn-on and turn-off times. It can also be seen that increasing the number of sequentially connected keys only worsens this picture. Thus, dynamic balancing of these chains, which consists in maintaining the parameters of both temporal and amplitude values of voltages on the switches throughout their operation, is necessary.

Ways to control series-connected chains of semiconductor devices are given below. A simplified version of cascade circuit (one of them) is shown in Fig. 4. It should be noted that in the complete circuit of the modulator key, there are voltage equalization circuits on the electrodes of semiconductor devices (see Fig. 3).

The switch is opened by applying a positive pulse to the gate of transistor X1(Q1). Opening this device leads to a decrease in the potential at its drain and an increase in the voltage at the gate of transistor X2(Q2) [7, 8]. The opening of this transistor leads to an avalanche-like opening process of the entire transistor's series chain due to a transistors gates potentials change. When the entire chain is fully open, the supply voltage is switched to the load. The avalanche-like process develops in the opposite direction when the key is closed. The duration of the avalanche process is determined by the rate of increase in the amplitude at each transistor gate and the switching time of each, starting from the bottom and ending with the top. When the entire chain is fully opened, the supply voltage is switched to the load. Avalanche-like process develops in the opposite direction when the key is closed.

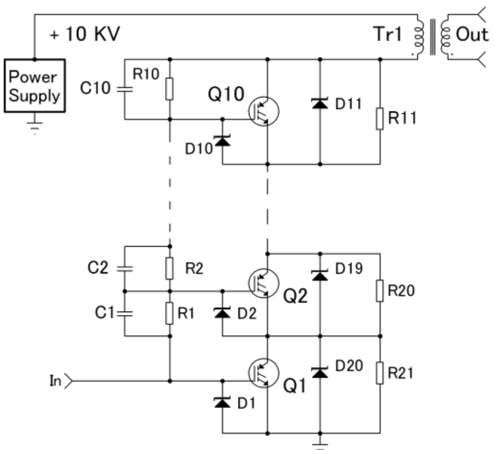

Fig. 4. Series connection of IGBT for high-voltage switching

Consider the process of turning on the transistor X2. As transistor X1 opens, the gate voltage of transistor X2 increases. The slew rate is determined by the resistance value in the gate circuit and the gate-source capacitance, which ranges from 5000 to 7000 pF. It should be noted that the IGBT opening threshold exceeds 6 V. This means that the duration of the avalanche process increases in proportion to the number of devices connected in series. In this case, the switching sequence of transistors is not necessarily from the bottom to the top. For the upper transistor, the opening process is similar to the previous one, but when it is opened, the power dissipated by the transistor increases sharply, leading to its failure. The spread of the parameters of all elements introduces changes in the order of switching on transistors, violating their sequence. The similar processes also occur when the chain is turned off.

Based on the above, we can conclude that the number used in high-voltage devices transistors, should be limited. At present, solutions to these problems by developing control the slew rate and voltage amplitude of at the gates are known. However, these circuit solutions are very complex and significantly complicate the practical implementation of high-voltage switches.

Another option for using high-voltage switches is to control each transistor with a separate driver. In this case, free from the shortcomings of the previous one, it becomes possible to simultaneously switch transistors. The operation of the keys becomes stable, since the cause of overvoltage's on the transistor electrodes disappears. In this version, the drivers must be galvanic ally isolated.

For galvanic isolation, an optocoupler or a transformer can be used. The optocoupler circuit requires a power supply and an amplifier at the source potential of the transistor, since the optocoupler does not supply the necessary power (current) to drive the gate. The use of a transformer provides sufficient control power but does not transmit a constant component. Therefore, to transmit the analog signal, a high-frequency carrier is used. The transformer driver must transmit the required power, have a small throughput capacitance, withstand the necessary operating voltages, and be manufacturable.

SCHEMATIC DECISION AND OPERATION FEATURES OF THE DEVELOPED NEW MODULATOR

Fig. 5 shows a high-voltage modulator, designed by us, to power the injector.

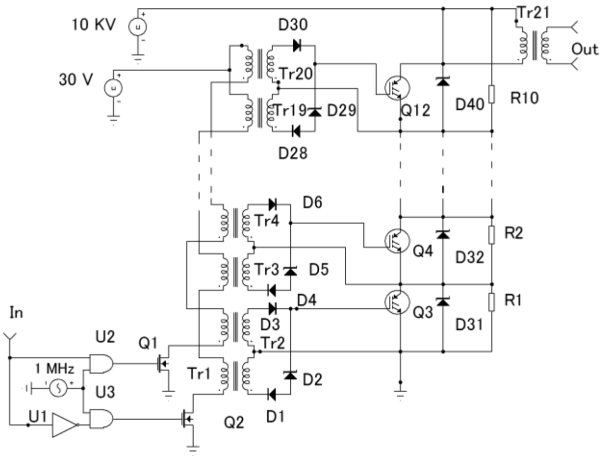

Fig. 5. Scheme of a high-voltage modulator

The high-voltage power switch consists of 10 (Q3…12) type series – produce IGBTs. This chain provides switching voltages up to 12 kV at currents up to 40 A. To protect transistors from overvoltage's, varistors with protective diodes are connected in parallel with them. The load of the modulator is a step-up high-voltage transformer, the secondary winding of which provides power to the 120 kV injector. To prevent breakdown, the high-voltage transformer is placed in oil. For fast switching of transistors, a transformer driver which develops high currents at the output is used.

The modulator (see Fig. 5) works as follows. A switch is assembled on U1…U3 microcircuits, which switches signals with a frequency of 1 MHz to transistors Q1 or Q2. The load of transistors Q1 and Q2 are transformers, the secondary winding of which contains rectifiers, providing the state of the IGBT. When an external trigger signal is present at the input (In), the IGBT circuit opens, switching the supply voltage to the transformer. At the end of the trigger pulse, the IGBTs are closed. Switching processes occur simultaneously, which ensures synchronous operation of all IGBTs. Such an algorithm of operation excludes the sequential switching on of devices and sharply reduces the power dissipated when switching devices. The duration of the pulse at the output of the modulator (Out) is determined only by the duration of the trigger pulse.

The load of the modulator is a high-voltage step-up transformer Tr21. A voltage of 120 kV from the secondary winding is supplied to the injector. Tests carried out on the breadboard showed that within the duration of the output pulse of 300…2000 μs, the modulator can switch a voltage of 10 kV at a load of 20 A.

CONCLUSIONS

The main solutions for the construction of high-voltage semiconductor modulators with a smooth change in the duration of the output pulse are considered. An analysis of the available semiconductor element base was carried out. The possibilities of using various devices for constructing high-voltage switches are considered. An analysis of the reasons for the failure of chains of IGBT transistors when they are connected in series and ways to protect them is given. A scheme of a high-voltage modulator is proposed that makes it possible to generate pulses with a duration of 300…2000 μs at the output at a voltage of 10 kV and currents up to 20 A.

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ВИСОКОВОЛЬТНИЙ МОДУЛЯТОР ДЛЯ ІНЖЕКТОРА ЛІНІЙНОГО ПРИСКОРЮВАЧА ІОНІВ З ПЛАВНИМ КЕРУВАННЯМ ТРИВАЛІСТЮ ІМПУЛЬСА

О.В. Мануйленко, В.А. Сошенко, О.В. Заботін, Б.В. Зайцев, В.Г. Журавльов

Стабільна робота лінійних прискорювачів іонів істотно залежить від режиму роботи іонного інжектора. Для забезпечення максимального захоплення пучка іонів, що вводиться у прискорювальну структуру, інжектор повинен мати можливість регулювати параметри пучка. Описана розроблена нова система живлення інжектора, побудована на сучасних вузлах, що дозволяє плавно змінювати тривалість імпульсу модулятора в діапазоні 300…2000 мкс. Проведено аналіз і усунено недоліки попередніх систем. Очікуване збільшення струму пучка прискорених іонів становить 15…20%. Пов’язані з цим результати включають зменшення ємності паразитного навантаження імпульсних пристроїв, зменшення розміру та відмову від високовольтних роздільних трансформаторів, що підвищує надійність прискорювача.