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IMPROVEMENT OF HELIUM IONS BEAM FORMATION AND TRANSPORT SYSTEM

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Works on improvement of a beam formation and transport system from an accelerating section output to the target complex on NSC KIPT helium ions linear accelerator with output energy of 4 MeV, used for carrying out of radiating researches are continued. Results of researches spent with electromagnetic quadrupole lenses, forming a triplet are presented. Experiments with injected (120 keV) and accelerated (4 MeV) helium ions beams by means of advanced beam formation and transport system to a target are continued. The proposal on decrease in thermal loading of a triplet is formulated.

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INTRODUCTION

Experiments on the new section intended for He^+ (A/q = 4) ions acceleration with 120 keV injection energy and 4 MeV output energy proceed. This section is used for carrying out of applied researches with output energy of 4 MeV (helium ions linear accelerator). Its basic elements are: an injector, resonator with an accelerating structure, placed in a vacuum tank (Fig. 1), and beam formation and transport system from an accelerating section exit to the target chamber with accompanying diagnostic devices for carrying out of radiating researches (Fig. 2) [1]. A special feature of the accelerating structure section is a use of an alternating-phase focusing variant with step-by-step change in a synchronous phase and increasing radio-frequency field amplitude in accelerating gaps on a grouping part of an accelerating-focusing tract [2 - 4].

Originally chosen variant (*a*) of a beam formation and transport system from an accelerating section output to the target chamber represented a triplet consisting of one long quadrupole lens and two short lenses on each side (see Fig. 2). This variant has given the chance to solve a problem of a beam current density increase, but did not allow long time working.

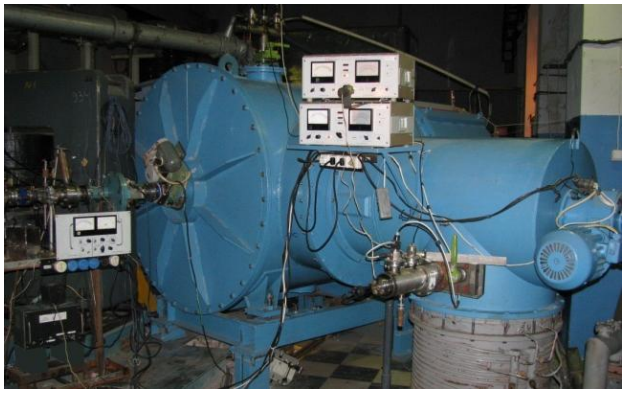

Fig. 1. Helium ions linear accelerator with output energy 4 MeV

The work purpose is carrying out numerical and experimental researches of various variants of formation and transport system improvement of helium ions accelerated beam with minimum losses and maximum beam density to a target complex intended for a performance of radiating researches at a long irradiation of samples.

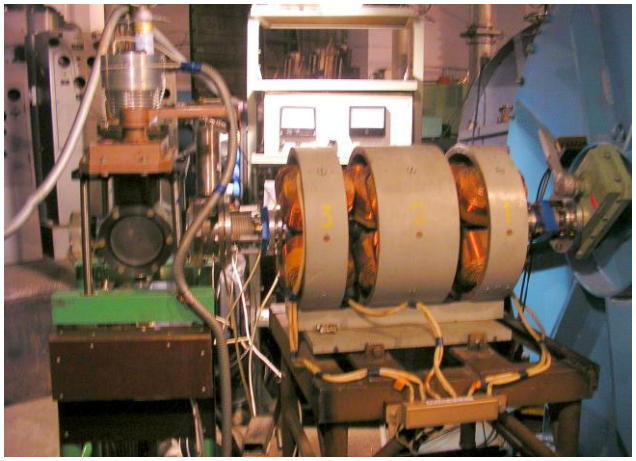

Fig. 2. Initial variant (a) of a beam formation and transport system from an accelerating section output (on the right) to the target chamber (on the left)

PROBLEM STATEMENT

The conducted researches of triplet quadrupole lenses, and also parameters injected (energy of 120 keV) and accelerated (energy of 4 MeV) helium ions beams have shown that the offered of beam formation and transport system on helium ions accelerator output allows to considerably increase of a beam current density on a target and approach to as much as possible value (at the existing equipment) (in detail described in paper [1]). But there was a problem of a thermal mode of quadrupole lenses long time working. The optimum mode on of a beam current density was reached at considerable values of power supplies quadrupole lenses currents (to 10 A). It demanded application of their cooling (for example, air).

The beam transport line between sections PSS-15 and BS-5 consisting of 3 triplets and a doublet which has successfully worked some number years, did not demand any cooling as currents values of power supplies on the majority of lenses (8) were to 2 A and only on last triplet (on a beam course) were to 6 A.

Therefore there was a problem of carrying out numerical and experimental researches of various variants of formation and transport system improvement of helium ions accelerated beam to provide of an accelerator long work mode.

CALCULATION OF THE TRIPLET FOCUSING CHANNEL

For performance of an assigned task the decision to use available equipment, i. e. other two similar triplets is accepted. It is offered to replace gradually two extreme short quadrupole lenses on two long (variants *b* and *c*).

For calculation of the transport channel with a focusing triplet and particles dynamics in it beam settlement characteristics on output of applied accelerating structure with an alternating-phase focusing, received by means of code APFRFQ were used: 4 MeV beam energy, 4 мА beam current, 30 mm beam diameter, 0 mrad slope angle of beam envelope [5, 6]. As a result of calculation and optimization of triplet main parameters: selection of drift intervals lengths and magnetic field gradients in lenses amounts for a transport channel geometry, values of magnetic field gradients in electromagnetic quadrupole lenses have been received and particles dynamics in such channel is calculated.

Beam envelopes (horizontal envelope is a dark blue, continuous line and vertical envelope is red, a dashed line), received for the chosen geometry of the channel (variant *b*) by means of code Trace-3d [7] are presented in Fig. 3. By numerals are designated: drift intervals: 1 – 100 mm, 3 – 75 mm, 5 – 70 mm, 7 – 250 mm; poles electromagnetic quadrupole lenses: 2, 4 – 180 mm, 6 – 90 mm. Magnetic field gradients created in quadrupole lenses: 2 – (–7.5) T/m, 4 – (+15.25) T/m, 6 – (–20) T/m.

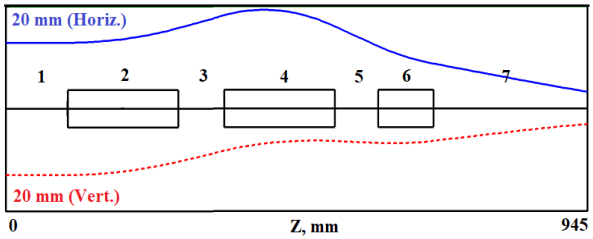

Fig. 3. Calculation results of a transport channel of helium ions beam from an accelerating section output (at the left) to a target (variant b)

Beam envelopes (horizontal envelope is a dark blue, continuous line and vertical envelope is red, a dashed line), received for the chosen geometry of the channel (variant *c*) by means of code Trace-3d [7] are presented in Fig. 4.

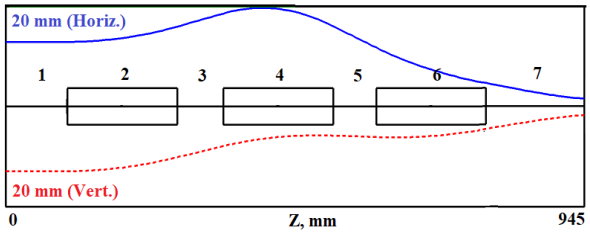

Fig. 4. Calculation results of a transport channel of helium ions beam from an accelerating section output (at the left) to a target (variant c)

By numerals are designated: drift intervals: 1 – 100 mm, 3 – 75 mm, 5 – 70 mm, 7 – 160 mm; poles electromagnetic quadrupole lenses: 2, 4, 6 – 180 mm. Magnetic field gradients created in quadrupole lenses: 2 – (–8) T/m, 4 – (+16) T/m, 6 – (–15,1) T/m.

Transfer to variant *c* allows not only to lower the maximum gradient of a magnetic field in last lens, but also to reduce beam diameter. The settlement results received on idealized model, can several differ from experimental values.

RESEARCH OF THE TRIPLET THERMAL MODE

Calculation results of a triplet focusing channel for variants *b* and *c* were verified in actual conditions.

Variants *b* and *c* of a beam formation and transport real system are respectively presented in Figs. 5, 6.

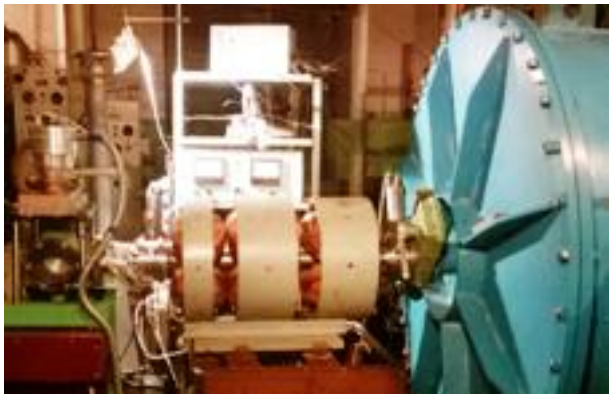

Fig. 5. Variant (b) of a beam formation and transport real system

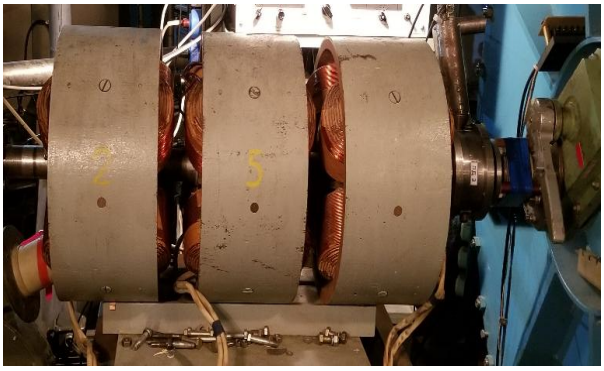

Fig. 6. Variant (c) of a beam formation and transport real system

The spent experimental researches have allowed finding optimum currents on focusing lenses of a triplet in various variants of its execution, at which beam density on a target becomes maximum. As in an initial variant *a* there are enough great currents values on quadrupole lenses led to their fast warming up – the temperature reached 100°C, and at a variant *c* temperature did not exceed 50°C at accelerator work in one shift (an order of 6 h) that the focusing variant *c* has been selected (values of currents are resulted in the Table). At longer work of the accelerator last quadrupole lens on a course of a beam demanded air cooling.

Optimum values of currents in lenses

Variant	Current, A		
a: S + L + S	6.6	6.7	10
c: L + L + L	3.2	5.8	5.6

By results of spent experimental researches and calculations the definitive variant (*c*) of a beam following channel to a target complex is formed.

PROPOSITION ON DECREASE IN THERMAL LOADING OF THE TRIPLET

Cardinally to solve a problem of a triplet thermal mode it is possible by transfer to pulse power supplies of quadrupole lenses. It will allow not only it is essential to lower thermal heating of quadrupole lenses coils, but also to reduce power consumption, respectively. This transition will not demand considerable expenditures as there is a possibility to use the available equipment and materials.

The quadrupole lens has 4 current windings which calculated on currents to 10 A. At consecutive connection of windings the general inductance makes 0.6 H and resistance on a direct current – 6 Ω. At parallel connection of windings the general inductance makes approximately 0.0375 H and resistance on a direct current – 1.5 Ω.

The function scheme consists of 7 modules (Fig. 7). Schemes modeling of quadrupole lens initial excitation were made in program Micro-Cap 9. The module of the entrance power filter <PS Filtr> is intended for protection of all block against pulse hindrances at work of the charged particles accelerator. Also in it soft start function <PS Soft Start> for power transformer inclusion is realized at initial charging of all power rectifiers condensers.

The transformer has a primary winding on ~220 V and 6 secondary windings for all block power (2* ~6 V, 2* ~14 V, ~36 V, ~200 V). The general pulse capacity can reach to 1000 W.

The module of rectifiers and voltage stabilizers +/–5 V, +/–15 V are intended in order to receive of power voltages of digital and analogue microcircuits in block management modules.

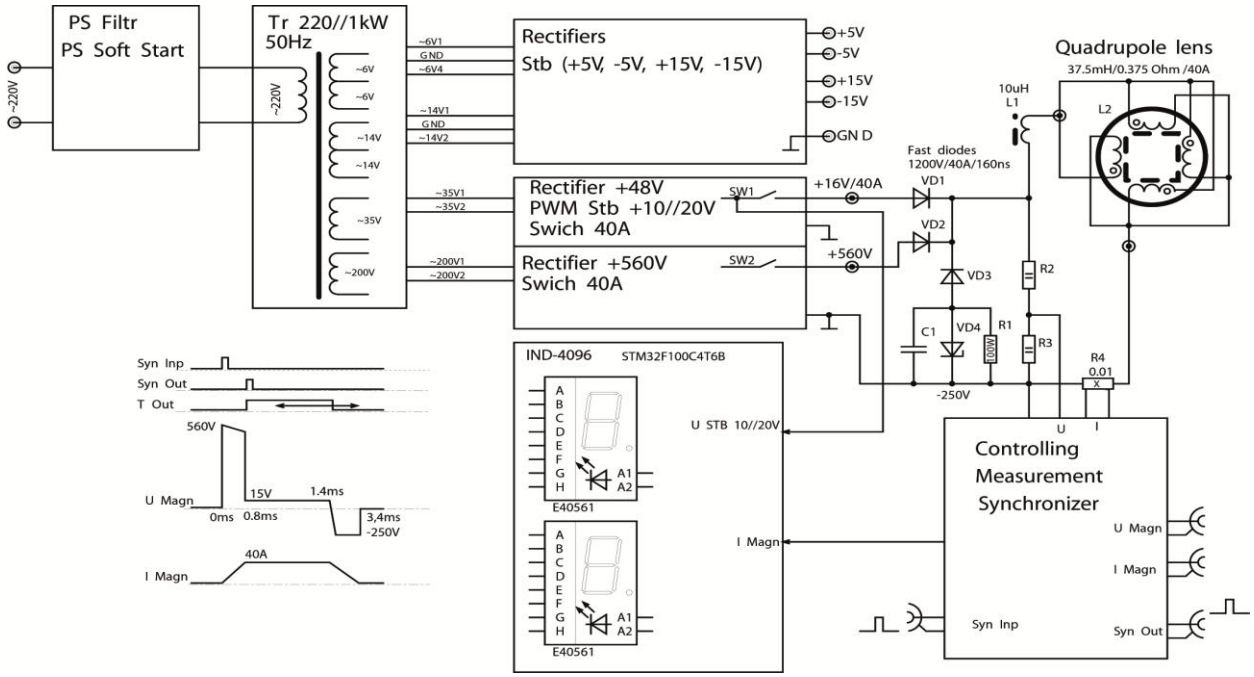

Fig. 7. Function scheme of the quadrupole lens pulse power supply

The module of the rectifier and voltage stabilizer +16 V/40 A is intended for a power by the stabilized current of quadrupole lens during an impulse of the accelerator work (from 100 to 1000 μs). The stabilizer is realized under the scheme of pulse-width modulation (PWM) with high efficiency. On a stabilizer output there is a power key with possibility of switching-off from loading.

The module of the rectifier +560 V/40 A is intended for initial fast riding up of a quadrupole lens power current (from 0.5 to 2 μs). The rectifier is realized under the voltage doubler scheme with accumulative condensers charging to +560 V and a power key with possibility of switching-off from loading. The condensers capacity of a voltage doubler is chose from level 5% of voltage droop during initial fast riding up of a quadrupole lens power current. The riding up voltage value is selected from a condition of the winding electric strength from lens keeper and the maximum breakdown voltages of power output keys (it is recommended IGBT transistors with a current not less than 50 A and breakdown voltages not less than 1200 V).

The management module is intended for development of all block control signals. On synchronization from the timer of the pulse accelerator there is an inclusion of voltage sources +560 V/40 A and +16 V/40 A. Through summarizing diodes VD1 and VD2 these voltages arrive on quadrupole lens. The source +16 V/40 A automatically turn on in loading only at achievement of lens riding up current of the established value (for example 40 A) and the source +560 V/40 A switching-off. A current is measured on the shunt after the scheme of the tool differential amplifier and the fast comparator. After that the readiness impulse for start of the accelerator work is generated. At consecutive connection of quadrupole lens windings their inductance can reach of 0.6 H and time of current riding up can reach 13 ms (at a current 10 A), and time current resorption to 5% at recuperation through diode VD3 (without R1, C1, VD4) to be not less than 1 s. This is very big time at impulses following frequencies to 10 Hz. It is more preferable to

use parallel connection of quadrupole lens windings with the general inductance to 37.5 mH and resistance of losses on a direct current 0.375 Ω. Thus current riding up time decreases to 800 μs (a current 40 A). The time current resorption to 5% at recuperation through diode VD3 and R1, C1, VD4 at stabilitron voltage 250 V it is possible reduce to 2 ms. At the same time almost all energy which has been saved up in quadrupole lens, will be emitted on external loading and it will reduce heat release in quadrupole.

The quadrupole stable impulse width is chose of accelerator working conditions. Approximately in this impulse middle storing of a lens current and its indication on the additional indicator (the indication module) is made. Also voltage indication on the stabilizer output +16 V/40 A (too with storing in the same time of sample) is made.

To operate the block in regular work on the accelerator it is recommended by means of the microcontroller of STM32 series with communication on an optical cable. Fine tuning of a lens current at warming up of the copper coil is thus possible. Throttles PWM of a regulator should be execute from a multicore wire.

CONCLUSIONS

Necessary elements are made, the advanced system of formation and transport of helium ions beam from an accelerator output to a target is calculated, developed, collected and adjusted. The conducted researches have shown that the offered system of a beam formation and transport on output of helium ions accelerator allows to essentially increase of a beam current density on a target and approach to as much as possible value (at the existing equipment) for carrying out of experimental researches at a long irradiation of samples. Proposition on decrease in thermal loading of a triplet that will allow to solve cardinally a problem of its thermal mode at long work is formulated.

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УСОВЕРШЕНСТВОВАНИЕ СИСТЕМЫ ФОРМИРОВАНИЯ И ТРАНСПОРТИРОВКИ ПУЧКА ИОНОВ ГЕЛИЯ

А.Ф. Дьяченко, С.Н. Дубнюк, О.В. Мануйленко, С.С. Тишкин

Продолжены работы по усовершенствованию системы формирования и транспортировки пучка с выхода ускоряющей секции к мишенному комплексу на линейном ускорителе ионов гелия ННЦ ХФТИ с выходной энергией 4 МэВ, используемого для проведения радиационных исследований. Представлены результаты исследований, проведенных с электромагнитными квадрупольными линзами, образующими триплет. Продолжены эксперименты с инжектируемым (120 кэВ) и ускоренным (4 МэВ) пучками ионов гелия с помощью усовершенствованной системы формирования и транспортировки пучка к мишени.

УДОСКОНАЛЕННЯ СИСТЕМИ ФОРМУВАННЯ ТА ТРАНСПОРТУВАННЯ ПУЧКА ІОНІВ ГЕЛІЮ

О.Ф. Дьяченко, С.М. Дубнюк, О.В. Мануйленко, С.С. Тішкін

Продовжено роботи з удосконалення системи формування й транспортування пучка з виходу прискорювальної секції до мішеневого комплексу на лінійному прискорювачі іонів гелію ННЦ ХФТІ з вихідною енергією 4 МеВ, що використовується для проведення радіаційних досліджень. Подано результати досліджень, проведених з електромагнітними квадрупольними лінзами, які утворюють триплет. Продовжено експерименти з інжектуємим (120 кеВ) і прискореним (4 МеВ) пучками іонів гелію за допомогою удосконаленої системи формування та транспортування пучка до мішені.