RECONSTRUCTION OF LIGHT AND POLARIZED ION BEAM INJECTION SYSTEM OF JINR NUCLOTRON-NICA ACCELERATOR COMPLEX

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The NICA ion collider project at JINR is under development at present. As a part of the project the Nuclotron injector upgrade has been started. The work is provided in cooperation of JINR, MEPhI and ITEP. Up to now the Nuclotron injection system consist of a number of proton and ion sources, the 650 keV pulsed preinjector and DTL linac LU-20 (Alvarez type). Such system provides injection into Nuclotron of 20 MeV proton and 5 MeV/u (Z/A >0.3) ion beams. The ion beam acceleration is realized at the 2nd harmonic of bunch travelling mode. The 650 kV high-voltage platform will be replaced by new RFQ structure. The R&D of this system is discussed in the report. Results of beam dynamics simulation in RFQ and MEBT between RFQ and LU-20, electrodynamics simulation, construction of RFQ resonator, RF feeding system construction will be presented. The RF power system is assembled and tested at equivalent load and RFQ resonator manufacturing is started.

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INTRODUCTION

The new accelerator complex NICA (Nuclotron-based Ion Collider facility) is now under development and construction at JINR. The injection system of the operating heavy ion superconducting accelerator Nuclotron is upgrade is planned. Moreover, construction of the booster ring, the collider rings and two particle detectors (MPD and SPD) is in progress (Fig. 1).

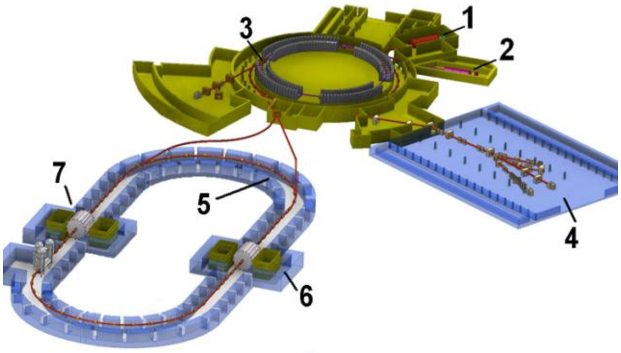

Fig. 1. Scheme of NICA facility: 1 – light and polarized ion sources and "old" Alvarez-type linac LU-20; 2 – ESIS source and new linac; 3 – Synchrophasotron yoke, Booster and Nuclotron; 4 – Nuclotron beam lines and fixed target experiments area; 5 – the collider rings; 6 – SPD; 7 – MPD

General goal of the NICA project is experimental studies of both hot and dense strongly interacting baryonic matter and spin physics in collisions of heavy ions and polarized protons and deuterons [1 - 4]. The first task of the program requires heavy ion collisions in the energy range of $\sqrt{S_{NN}}$ = 4…11 GeV at an average luminosity of $L=1\cdot10^{27}$ cm^{-2}c^{-1} for $_{197}$Au^{79+} nuclei. The polarized beams mode is proposed to be used in the energy range of collision energy of protons $\sqrt{S}$ =12…27 GeV and deuterons $\sqrt{S_{NN}}$ = 4…13.8 GeV (2…5.9 GeV/u ion kinetic energy) at an avarege luminosity $L \geq 1\cdot10^{31}$ cm^{-2}c^{-1}.

The NICA project assumed to operate using two injectors [5]: the Alvarez-type linac LU-20 as injector for light ions, polarized protons and deuterons and a new linac HILac for heavy ions. The Electron String Ion Source (ISIS) is planned for ion beam generation meanwhile the Source of Polarized (SPI) is planned for polarized proton and deuteron beam generation [6]. Upgrade of LU-20 front end is described.

1. LU-20 INJECTION LINAC UPGRADE PROGRAM

Alvarez-type DTL linac LU-20 used as the Nuclotron injector. was put into operation in 1974. It was originally designed as the proton accelerator. Protons can be accelerated by LU-20 from 600 keV to 20 MeV. Later it was modified to accelerate ions with charge-to-mass ratio Z/A>0.3 due to modification of operational mode from $L = \beta\lambda$ to $2\beta\lambda$. That made it possible to accelerate also ions up to 5 MeV/u [7].

The pulse transformer with voltage up to 700 kV is now used to feed the accelerating tube of the LU-20 forinjector. The ion sources used up to now and placed at the HV "hot" platform consumes up to 5 kW power, which is provided by feeding station consisting of motor and generator insulated one from the other with wood shaft. Power consumption of the new ion sources is ~15 kW for ESIS and ~25 kW for SPI [6]. Such power level can not be provided by the existing system. The new fore-injector will be based on radio-frequency quadrupole linac (RFQ). Replacement electrostatic tube with RFQ will allow to decrease potential of the "hot" platform and to use the insulation transformer to feed the sources. High voltage (up to 150 kV) DC power supply will be used to provide necessary electric potential. Installation of two separate RFQ (for *Z*/*A*=1 and *Z*/*A*=0.3…0.5) can be made to cover the necessary range of particles charge-to-mass ratio [6]. The RFQ section parameters are shown in Table 1.

Table 1

The forinjector design parameters

Forinjector Input			
Z/*A*	1.0	0.5	0.3
Injection energy, keV	≤150	61.8	103
Maximum current, mA	40	20	10
Normalized transverse emittance, π·cm·mrad	0.4	0.2	0.15
Operating frequency, MHz	145.2		
Output			
Output energy, MeV/u	0.631	0.156	0.156
Transmission RFQ, %	≥ 80	≥85	≥90
Δ*p*/*p*, %	≤ 6	≤ 4	≤ 4
Normalized transverse emittance, π·cm·mrad	≤ 1.0	≤0.5	≤ 0.5
Resonator length, m	≤ 3	≤ 3	≤ 3
Voltage at electrodes, kV	126	84	140

The new RFQ linac project is performed in collaboration of JINR, MEPhI and ITEP. The beam dynamics simulation, RF resonator simulation, construction and drawing and RF system development and manufacturing are finished till present. The accelerating resonator is now under manufacturing at VNIITP (Snezhinsk). Let we discussed the main R&D results.

2. BEAM DINAMICS IN RFQ RESONATOR

The results of beam dynamics simulation and RFQ channel parameters definition are discussed in detail later. It wills very complex goal to achieve the project parameters because of very low output energy and high injection beam emittance and leads to non conventional RFQ linac design.

Table 2

Beam dynamics simulation parameters

Z/*A*	0.3	0.5
Injection and output energy, keV/u	31…155	
Normalized acceptance, π·cm·mrad	0.5	
Normalized emittance, π·cm·mrad	0.15	0.2
Limiting current (simulated), mA	190	114
Transverse oscillations phase advance, deg	26.5	
Longitudinal oscillations phase advance, deg	23.5	
Synchronous phase, deg	-90…-40	
Output pulse spectrum, %	± 2.5	
Averaged distance of electrode from the axis, mm	6.5	
Electrodes modulation coefficient	1.28	
Aperture radius, mm	5.7	
Cells number	194	
Linac total length, mm	2070	
Current transmission coefficient, % without/with buncher	91/ 93	88/ 89
Transverse emittance growth, without/with buncher	1.33/ 1.25	1.18/ 1.14
Longitudinal emittance growth, without/with buncher	2.89/ 1.96	2.89/ 1.61

The scheme of accelerating-focusing RFQ channel consists of matching, bunching, main accelerating and debunching sub-sections. The main channel and beam parameters were defined by analytical model and beam dynamics simulation and are presented in Table 2. The parameters of channel were choosing by the method proposed in [8].

The beam dynamics simulations were done using codes RFQDYN, DYNAMION [9] developed at ITEP and LIDOS [10] developed at MRTI RAS. Two possible schemes were discussed: without of matching resonator (buncher) before RFQ resonator and with such buncher. The results of simulation are presented in Table 2 and Figs. 2, 3.

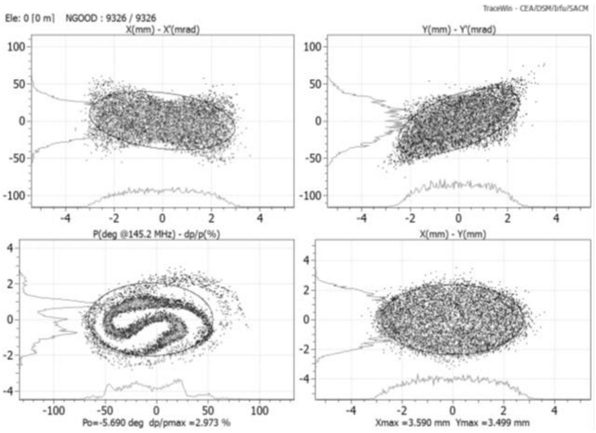

Fig. 2. Output particles distribution in transverse and longitudinal phase planes, Z/A=0.3, without matching resonator

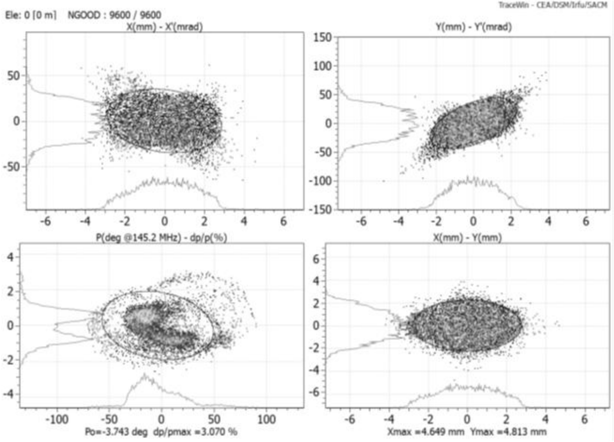

Fig. 3. Output particles distribution in transverse and longitudinal phase planes, Z/A=0.3, with matching resonator

It is clear that the matching resonator sufficiently decrease the output beam emittance. The current limit of the structure was also defined by simulation (Fig. 4).

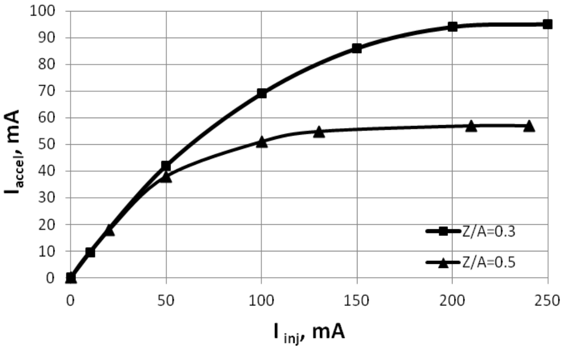

Fig. 4. Current transmission versus injection current

3. RFQ – LU-20 MATCHING CHANNEL

Matched channel should provide total beam re-capturing in the next section. But in our case it is very serious problem because of long transport base between the RFQ end and the first LU-20 drift tube (corresponding to the LU-20 vacuum system parameters) and low injection energy of LU-20. Seven different matching schemes were simulated to obtain high recapturing efficiency. The most common matching scheme is presented in Fig. 5. Such scheme includes up to three bunchers (before RFQ R, after RFQ B1 and into vacuum seal of LU-20 B2). Two magnet quadrupole triplets (Q1-Q6) are used for transverse beam matching.

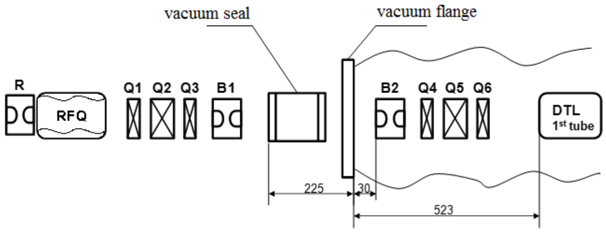

Fig. 5. Matching system scheme

It was shown by simulation that the optimal matching can be achieved using only R and B1 without B2 buncher. Up to 90% of injected into RFQ ions for *Z*/*A*=0.3 and 87% for *Z*/*A*=0.5 are effectively transported to the first LU-20 drift tube and 79% for *Z*/*A*=0.3 and 71% for *Z*/*A*=0.5 will injected into measured LU-20 acceptance. Transverse losses are very low in transport and all of them are due to longitudinal bunch size enlargement. Using of the third buncher no gives no some advantages but makes very seriously complex vacuum and RF systems much more complicated.

4. RFQ RESONATOR

The four-vane resonator with displaced magnetic coupling windows [11] was chosen for NICA the RFQ design. Operating frequency is of 145.2 MHz and such frequency is defined by the LU-20 main resonator operating frequency. The simulations of electrodynamics characteristics of the resonator were done using CST Studio Suite code. The models of one resonant cell and 3D model of whole resonator (Fig. 6) were designed and studied. The resonator consists of nine resonant cells, seven of them are identical and two are the end cells with modified coupling windows.

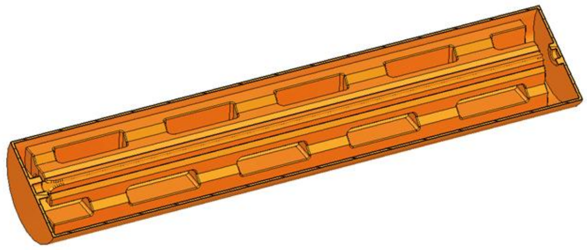

Fig. 6. RFQ resonator model

The simulations were directed to match the cells to the operating frequency and to minimize the deviation of RF field amplitude. Both problems were solved and the amplitude deviation is not higher than ±0.25% (Fig. 7). The tolerances of the electrodes manufacturing must be less than ±25 µm (±0.39% of averaged aperture radius) whereas and the constructional errors are two times lower of them.

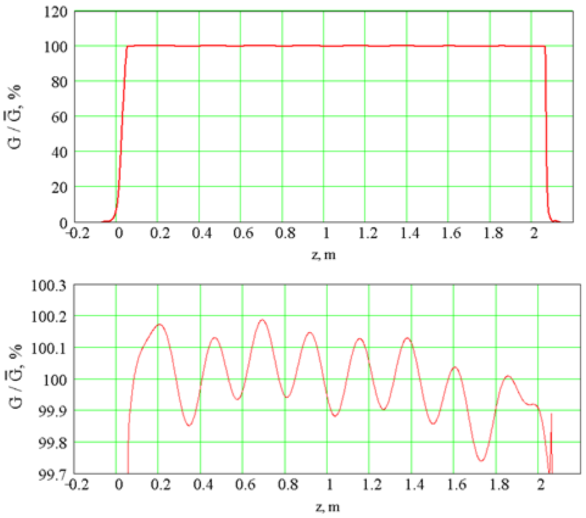

Fig. 7. Inter-electrode voltage distribution along resonator

Unfortunately, the simulation can not guarantee that the resonator will have exact value of operating frequency. That is why the resonator has been simulated for a little bit higher resonant frequency (146.6 MHz) in order to find operating frequency by means of enlargement of the windows size. The resonator has been simulated for a little bit higher resonant frequency (146.6 MHz). After first assembling of resonator for electrodes adjusting the frequency measurements will be carried out. According to the measured result the final electrodes windows dimensions will be defined to provide the resonance frequency from region 149.9≤f≤145.1 MHz. The resonator parameters after optimization are presented in Table 3.

Table 3

RFQ resonator parameters

Length of electrodes, mm	2070
Total length of resonator, mm	2190
Diameter of resonator, mm	400
Transverse size of coupling window, mm	62
Longitudinal size of coupling window, mm	288
Resonant frequency before tuning, MHz	146.6
Operating frequency, MHz	145.2
Dipole mode frequency, MHz	156.4
Voltage at electrodes, kV	125
Q-factor	9300
RF loses, kW	200
RF field amplitude deviation, %	< 0.5
Transverse component of RF field deviation, %	<±0.18
Maximal electric field on surface, MV/m	24

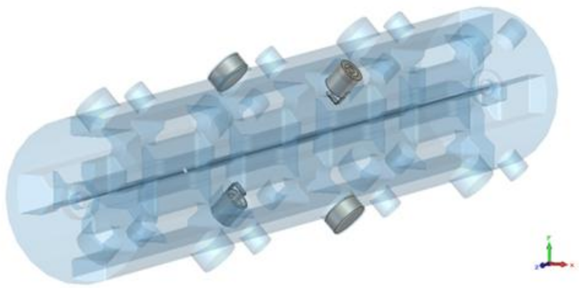

Fig. 8. Model of RFQ resonator with plungers and RF couplers

The fine operating frequency tuning can be done using two plungers (tuners) which are constructively placed in the middle of resonator (Fig. 8). The frequency sensitivity to the plunger motion is about 7 kHz/mm. Hence, 50mm–movement of the plungers will allow to tune the frequency in 300 kHz range.

5. RFQ RESONATOR DESIGN AND MANUFACTURING

The RFQ resonator engineering design was done and the drawings were designed as well (see 3D general view in Fig. 9). For the moment the resonator manufacturing is started at All-Russian Research Institute of Technical Physics (Snezhinsk) and expected to be finished by the end of 2013.

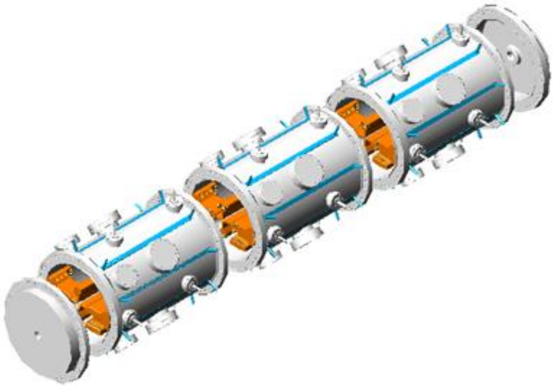

Fig. 9. 3D general view RFQ resonator

6. RF POWER SYSTEM

The design the RF power system is discussed more detailed in [12].

The LU-20 resonator is operating in self-excitation mode. This regime demands higher tolerances of RF field stability for LU-20 and RFQ resonators and to higher quality of automatic phase control system.

RFQ resonator RF power system consists of two amplifier channels for RFQ resonator and for buncher. High power systems include of low power master generator based on solid state preamplifier, first preamplifier based on four GI-39B tubes and high power final amplifying stage based on GI-27AM triode.

Buncher RF power system consists of solid state preamplifier and two stages based on GI-39B tubes because of low power necessary.

The control system should provide the RF field phase shift between DTL and RFQ resonators better than that one degree.

The amplifying stage based on GI-39B tube was tested to define maximal output power at operating frequency. The maximum power is equal to 30…35 kW with 150 μs RF pulse length. It is necessary to fed about 50 kW to excite the GI-27. Four pre-amplifying cascades based on GI-39 were manufactured and the combiner was designed.

The measured output pulse power P_n, consumed power P_0 and efficiency η versus anode potential U_a are shown in Fig. 10. Maximal amplification coefficient is equal to 8.5 and peak measured power is limited by 400 kW.

The high power pulse modulator was manufactured to form anode potentials.

Power system is manufactured, tested and is ready to routine operation. The photo of RF power system is shown in Fig. 11.

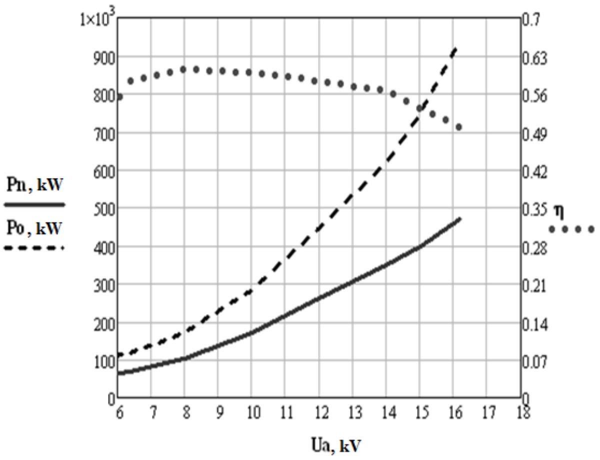

Fig. 10. Output pulse power P_n, consumed power P_0 and efficiency η versus anode potential

Fig. 11. Photo of RF power system

CONCLUSIONS

The reconstruction of light ion and polarized protons and deuterons beam injection system for Nuclotron-NICA accelerator complex is in progress. It is expected that high-voltage 700 kV platform, which is now used to feed the accelerating tube of Alvarez type linac pre-injector will replaced by RFQ section. The section should to bunch and to accelerate beams of ions with charge-to-mass ratio $Z/A>0.3$. This project is realized in cooperation o JINR, MEPhI and ITEP and was started in 2011.

The beam dynamics in RFQ and in matching system between of new RFQ and LU-20 was studied in detail. It was shown that up to 90% for $Z/A=0.3$ and 87% for $Z/A=0.5$ of ions are effectively transported to the first LU-20 drift tube and 79% for $Z/A=0.3$ and 71% for $Z/A=0.5$ are recaptured by LU-20. Using of matching resonator before RFQ and integrated debuncher into

RFQ provides the low emittance growth in RFQ and transport channel: lower than 25% for transverse emittance and lower than two times for longitudinal one.

The RFQ resonator based on known scheme using unsymmetrical coupling windows was designed. Tuning system was designed and simulated also. The RF field amplitude deviation is not higher than ±0.25% of the averaged value.

RF power system for RFQ and bunchers feeding is designed, manufactured and tested. The operating output power is equal to 400 kW which is about two times higher than is necessary for RFQ resonator according to simulation.

The RFQ resonator engineering design was done and now the structure is under manufacture at VNIITF. It is planned to finish the manufacturing in 2013.

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РЕКОНСТРУКЦИЯ СИСТЕМЫ ИНЖЕКЦИИ ПУЧКА ЛЕГКИХ И ПОЛЯРИЗОВАННЫХ ИОНОВ УСКОРИТЕЛЬНОГО КОМПЛЕКСА «НУКЛОТРОН-NICA»

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В настоящее время в ОИЯИ разрабатывается и реализуется проект коллайдера тяжелых ионов NICA, а также проводится необходимая реконструкция «Нуклотрона». В частности, сотрудниками ОИЯИ, МИФИ и ИТЭФ проводится реконструкция системы инжекции ионного пучка. В настоящее время система инжекции включает в себя несколько источников протонов и ионов, импульсный электростатический инжектор на 650 кВ и ускоритель Альвареца ЛУ-20. Эта система позволяет инжектировать в «Нуклотрон» пучки протонов с энергией 20 МэВ и тяжелых ионов с энергией 5 МэВ/нукл. При этом ускорение ионов в ЛУ-20 производится на второй кратности. В результате реконструкции высоковольтный инжектор должен быть заменен ускорителем-группирователем с пространственно-однородной квадрупольной фокусировкой (ПОКФ). Рассмотрен ход работ по созданию этого нового ускорителя. Представлены результаты моделирования динамики пучка в резонаторе с ПОКФ и канале согласования с ЛУ-20, результаты моделирования электродинамических характеристик ускоряющего резонатора и его конструирования, результаты разработки системы высокочастотного питания. В настоящее время система питания собрана и настроена на эквивалентную нагрузку, а резонатор с ПОКФ передан в производство.

РЕКОНСТРУКЦІЯ СИСТЕМИ ІНЖЕКЦІЇ ПУЧКА ЛЕГКИХ І ПОЛЯРИЗОВАНИХ ІОНІВ ПРИСКОРЮВАЛЬНОГО КОМПЛЕКСУ «НУКЛОТРОН-NICA»

В.А. Андрєєв, А.І. Балабін, А.В. Бутенко, В.С. Дюбков, А.І. Говоров, Б.В. Головенський, В.В. Кобець, А.А. Коломієць, В.А. Кошелєв, А.Д. Коваленко, А.В. Козлов, Г.Н. Кропачов, Р.П. Куйбеда, Т.В. Кулевий, В.Г. Кузмічов, К.А. Левтеров, Д.А. Лякін, В.А. Мончинський, А.С. Пластун, С.М. Полозов, А.В. Самошин, Д.Н. Селезньов, В.В. Селезньов, А.О. Сідорін, Ю.Б. Стасевич, Г.В. Трубников

В даний час в ОІЯД розробляється і реалізується проект коллайдера важких іонів NICA, а також проводиться необхідна реконструкція «Нуклотрона». Зокрема, співробітниками ОІЯД, МІФІ та ІТЕФ проводиться реконструкція системи інжекції іонного пучка. В даний час система інжекції включає в себе кілька джерел протонів і іонів, імпульсний електростатичний інжектор на 650 кВ і прискорювач Альвареца ЛУ-20. Ця система дозволяє інжектувати в «Нуклотрон» пучки протонів з енергією 20 МеВ і важких іонів з енергією 5 МеВ/нукл. При цьому прискорення іонів у ЛУ-20 виробляється на другий кратності. У результаті реконструкції високовольтний інжектор повинен бути замінений прискорювачем-групіпрователем з просторово-однорідним квадрупольним фокусуванням (ПОКФ). Розглянуто хід робіт зі створення цього нового прискорювача. Представлено результати моделювання динаміки пучка в резонаторі з ПОКФ і каналі узгодження з ЛУ-20, результати моделювання електродинамічних характеристик прискорюючого резонатора і його конструювання, результати розробки системи високочастотного живлення. В даний час система харчування зібрана і налаштована на еквівалентне навантаження , а резонатор з ПОКФ переданий у виробництво.