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Laser ion source in injection facility of NICA project

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Abstract

In the framework of the NICA project for the development of an accelerator collider facility at the LHEP JINR, Dubna, the design and commissioning of two injectors are under way. The Heavy Ion Linear accelerator (HILAC) is intended to inject the gold ions into the superconducting synchrotron Booster and designed to accelerate particles with a charge-mass ratio $Z/A \geqslant 0.16$ up to an energy of 3.2 MeV u^{-1}. HILAC in 2015 installed in the workplace in the hall of the injection facility. In 2018, a series of tests on HILAC commissioning had been done to measure the energy and estimate transmission of accelerated beams of the carbon ions from the laser ion source. The Light Ion Linear accelerator (LILAC) is intended for injection into the superconducting synchrotron Nuclotron the polarized deuterons and protons, as well as the light ions from LIS and is in the design stage for accelerating particles with a charge-mass ratio of $Z/A \geqslant 0.33$ to 7 MeV/u. The stable beam intensity from LIS is strongly desirable for the tasks listed above. The article describes the use of the beams from a laser ion source based on an Nd:YAG laser in the injection facility and presents a method for solving the problem of beam instability due to uncontrolled emission caused by reflected radiation.

Keywords: NICA, ion source, linear accelerator, HILAC commissioning

(Some figures may appear in colour only in the online journal)

1. LIS in injection facility

1.1. Experimental program overview

NICA accelerator collider facility (Nuclotron-based Ion Collider fAcility) is under construction for fundamental and applied physical researches using extracted and colliding ion beams with energies from several hundred MeV to several GeV and consists of two injectors based on linear accelerators, two superconducting synchrotrons, a Collider and beam transport channels. The extracted beams are planned to use at the radiobiological and applied physical research setups, also using the beams at the internal target of the Nuclotron is supposed. Two detectors will be built around interaction points where the particle beams will collide for the registration of the events from the heavy ions and polarized particles beams collisions (figure 1).

1.2. Experimental program

Experiments on the study of baryon matter, nature and properties of strong interactions, the search for possible confirmation of the signs of the mixed phase and the critical point will be carried out on colliding beams of heavy ions with an energy of up to 3.5×3.5 GeV u^{-1} and an average luminosity of 10^{27} cm^{-2}c^{-1} on a Multi-Purpose Detector (MPD), or on the derived beam of heavy ions at the BM@N (Barion Matter at Nuclotron) [1]. Ions of gold Au^{31+} will be

Figure 1. Layout of accelerating facility NICA [1].

accelerated to an energy of 600 MeV/u in a superconducting synchrotron booster, then, after passing the Stripping target, the acceleration of gold nuclei to the energy needed will be carried out in the synchrotron Nuclotron, and then the accelerated beam will be transferred to the Collider or output to the BM@N setup (figure 1). As injector to the booster beams of heavy particles to be used in a Heavy Ion Linear accelerator (HILAC), which consists of radio-frequency quadrupole (RFQ) and two DTL accelerating sections [2, 3], developed in the company Bevatech GmbH, Germany. Beams of the heavy ions with a high charge states will be produced by the ESIS 'KRION' electron-string source. This source was developed in JINR and based on the phenomenon discovered during the study of operating modes of the electron-beam source EBIS, operating in the reflective mode. It was found that under certain conditions, the 'cloud' of repeatedly reflected electrons enclosed in a strong solenoid magnetic field exhibits properties similar to the phase transition. This leads to a gradual increase in the electron plasma density and the transition to a new stationary state called the electron string [4]. The design of the source 'KRION' is in progress. In the accelerating run of the Nuclotron in 2018, the beams C^{6+}, Ar^{16+} и Kr^{26+} were used, and the operating modes of the source were investigated. Now the bench tests of the source to obtain heavy multi-charged ions are being carried out.

Experiments on research in the field of spin physics using the beams of polarized or unpolarized protons and deuterons will be carried out by SPD (Spin Physics Detector) of the collider or on the experimental setups using extracted beams. The beams of polarized protons or deuterons will be injected directly into the Nuclotron and after acceleration up to the energy needed will be transferred to the collider or extracted to the BM@N setup. As an injector into Nuclotron for the beams of polarized particles, the Light Ion Linear accelerator (LILAC) will be used. The LILAC, like the HILAC, is designed by Bevatech GmbH and consists of an accelerating section with radio-frequency quadrupole (RFQ) and two accelerating sections with drift tubes structure [5]. For the production of polarized protons and deuterons beams the source of polarized ions SPI (Source of Polarized Ions) was developed and put into operation in JINR in collaboration with the INR. In February-March 2017, the beams of polarized protons and deuterons from the SPI source were accelerated in the Nuclotron and their polarizations were measured for different operating modes of the source [6, 7].

Table 1. HILAC and LILAC main parameters

	HILAC	LILAC
Accelerated particles	Au^{31+}	p↑, d↑, light ions
Z/A	$\geqslant 0.16$	$\geqslant 0.33$
Input energy	17 keV/u	25 keV/u
Output energy	3.2 MeV/u	7 MeV/u
Beam current, mA	10	5 (p), 15 (C^{4+})
Operating frequency, MHz	100.625	162.500
Beam transmission rate, %	98	$\geqslant$80
Length of accelerator, m	9.4	9.8

Experiments using the beams of both light and heavy ions will also be at the station of the internal target. The wires, thin films (about 1 micron) of polyethylene or other materials, installed in the accelerator chamber are used as the targets. Using of gas jet targets technique has been developed (supersonic jet of hydrogen or another gas). The physical program includes experiments in the field of spin and relativistic physics, for example, the study of the formation of cumulative protons, deuterons, and K-mesons with emission angles from 30° to 135° [8].

The experiments are planned to collide beams of polarized deuterons and light nuclei. In this case the simultaneous operation of two injectors will be required: LILAC will supply beams of polarized deuterons from the SPI source, and HILAC - beams of light ions from the laser ion source (LIS). Both accelerators use an accelerating structure with 'KONUS' drift tubes [9]. The main parameters of both accelerators are shown in table 1.

1.3. Laser ion source

Beams of light ions from LIS are traditionally injected into Nuclotron in accelerating runs and extracted to physical setups for the radiobiological and applied researches. Within the framework of the injection facility upgrade, two new linear accelerators for injection of heavy and light ions will be put into operation. The SPI and KRION mentioned above are difficult to operate and energy consuming sources (figure 2), therefore a laser source will be used for commissioning of both accelerators. The beams from a LIS are also used for setting up the accelerators before the start of accelerating run.

The light ion laser source, developed at the JINR Laboratory of High energy physics in 1983, is based on a CO_2 laser. The principle of its operation is based on the extraction of ions from the laser plasma formed as a result of the action of a focused laser pulse on the target. The radiation flux density at the target was $\sim 10^{10}$ W/cm^2 and the spectrum of accelerated ions was $^6Li^{3+}$, $^7Li^{3+}$, B^{4+}, C^{4+}, N^{5+}, O^{6+}, F^{7+}, Mg^{8+}, Si^{11+}. To obtain the high charged ions an Nd:YAG laser was purchased to be implemented into the laser ion source. The expected laser radiation flux density at the target was estimated to be $\sim 10^{13}$ W/cm^2 [10]. Test bench was assembled to investigate the charge spectrum of the carbon

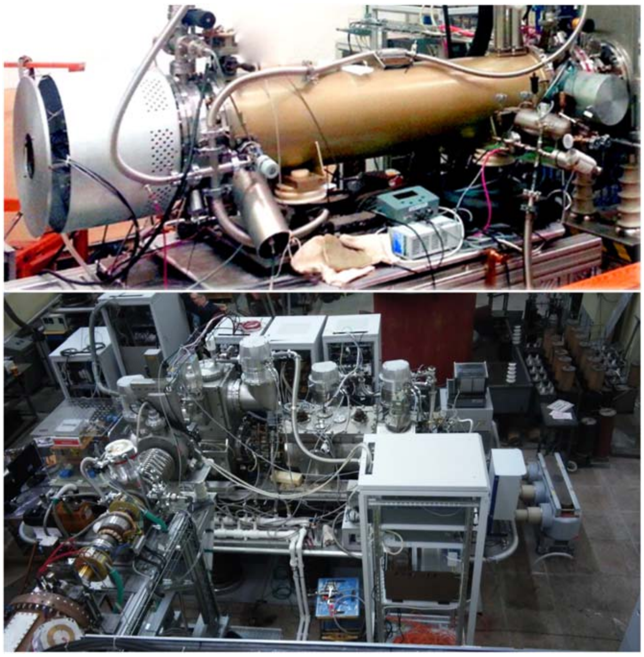

Figure 2. The Electron String Ion Sources 'KRION', total length 2 m (up); and Source of Polarized Ions (SPI) placed on the 3 × 3 m^2 'hot' platform (down).

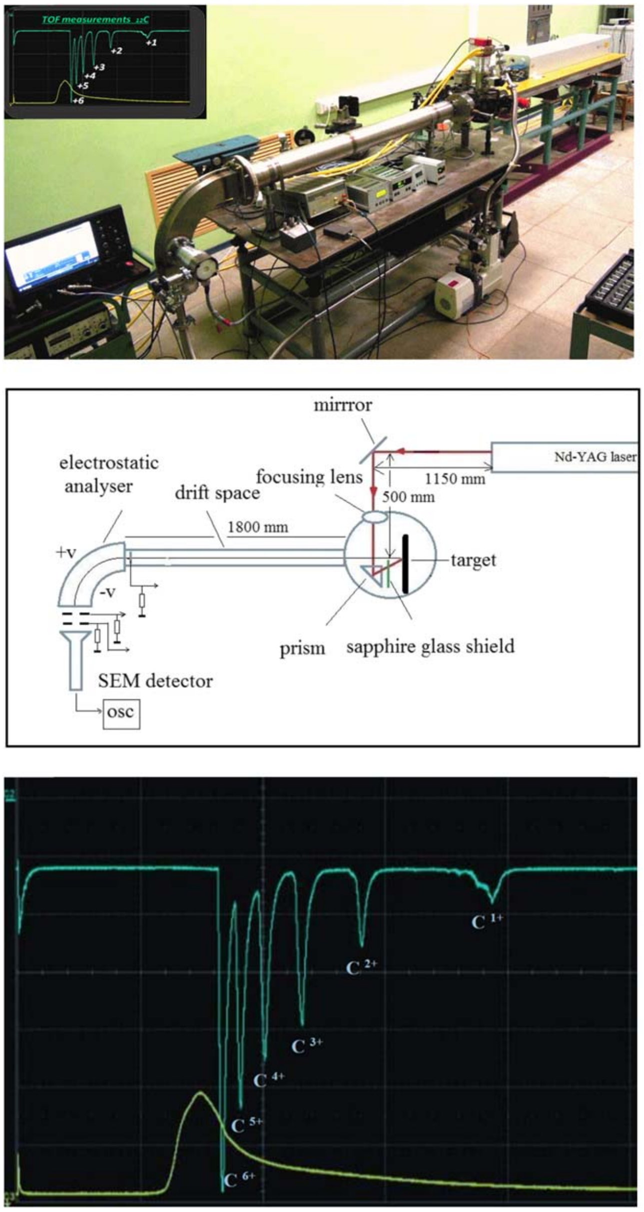

Figure 3. The laser test bench for investigating the charge spectrum of laser plasma from Nd:YAG laser (up), layout (middle), SEM signals behind electrostatic analyzer, 5 us/div (down).

plasma (figure 3). Output laser radiation was reflected from the mirror and focused on the investigated material by the meniscus lens embedded directly into the target chamber and vacuum sealed. The prism provided the incident angle 80° to bring it closer to 90° to increase the flux density on the target. Produced plasma spread through the drift space and get into electrostatic analyzer. The signals were registered behind analyzer with the secondary electron multiplier. The test bench experiments on the charged states spectrum investigation confirmed the presence of six charge states of the ions in carbon plasma (figure 3). Thus, the new laser source can be configured to produce both light ions of high charge states and ions with a low Z/A ratio for testing both linear accelerators.

2. The beams from the laser ion source for commissioning of the heavy ion accelerator.

The Heavy Ion Linear accelerator (HILAC) is intended for injection of gold ions Au^{31+} beams into the superconducting synchrotron and designed to accelerate particles with a charge-mass ratio $Z/A \geqslant 0.16$ up to energy 3.2 MeV u^{-1} (table 1).

In 2015, HILAC was installed on its workplace in the hall of the injection facility (figure 4). For commissioning of the accelerator, the extracted beams from a laser ion source based on Nd:YAG laser were transported to RFQ by the low energy beam transfer channel (LEBT) [11, 12]. From 2016 to 2018, a series of tests were carried out to measure the energy of ions accelerated in the HILAC and estimate the transmission.

The pulsed laser radiation was focused on the target by a meniscus lens with a focal length 125 mm. Energy in pulse was ~1 J, the duration ~10 ns and repetition rate 0.1–0.15 Hz. Carbon, deuterated polyethylene and polyethylene plates of 2–3 mm thickness fixed on the aluminium basement that could be moved with stepper motor in XY plan to set the operating spot into the center of the vacuum chamber where the radiation was focused to were used as targets. The duration of the beam current of ions entering the accelerator was about 15 μs. To obtain a stable beam with sufficient intensity at the output of the accelerator when it is tuned for the acceleration of ions with the given Z/A, it was necessary to choose such a laser radiation flux density at the target, which would ensure the maximum percentage of such ions in the laser plasma. The laser radiation flux density on the target was varied by tuning the distance between the focusing lens and the target operating spot and variation of the pulse energy (pumping level) of the

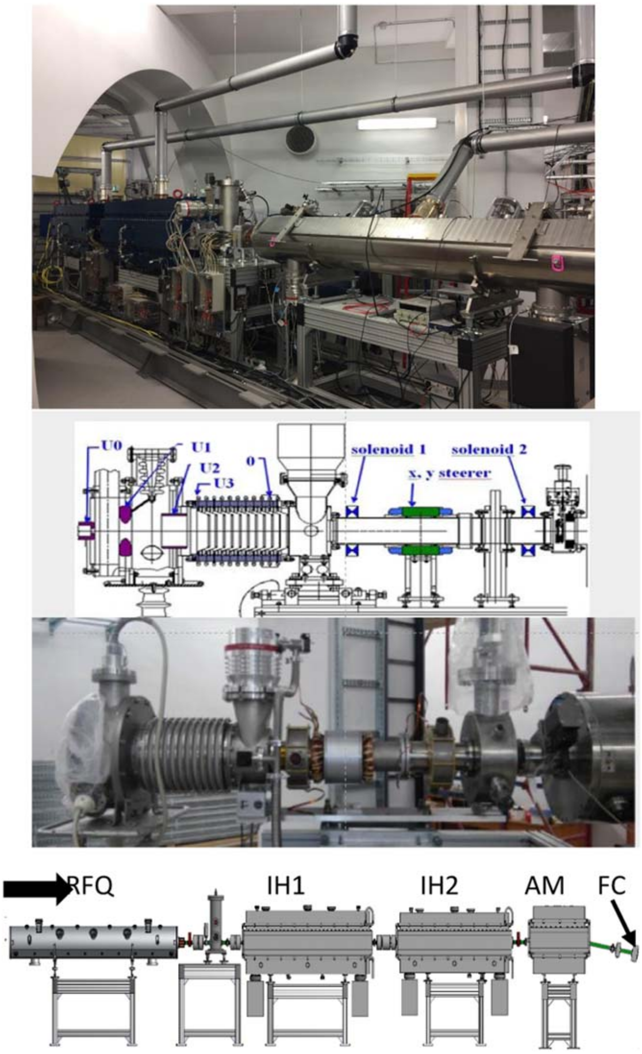

Figure 4. HILAC at the workplace (up), low energy beam transporting channel (LEBT) layout (middle), HILAC commissioning setup layout: AM-analyzing magnet, FC—Faraday cup (down).

laser and was chosen so as to register the maximum signal from the current transformer installed at the accelerator output. The stepper motor was used to move the focusing lens. The beam energy was controlled by a signal from the Faraday cup located behind the analyzing magnet at the accelerator output. It turned out that with a constant laser pumping level of 60%, to obtain sufficiently stable accelerated beams of C^{2+}, C^{3+}, C^{4+} (1.1 mA, 1.8 mA, 0,95 mA accordingly) the distance between the lens and the target operating point should be 5–10 mm longer than the focal length, i.e. laser radiation should be very defocused. Under this condition the 15%–20% drop of the average value of the beam current amplitude at the accelerator output was observed after 2–3 h (900–1400 pulses) without shifting the target for a new operating spot. If the lens was set closer to the target to reach defocusing effect the more or less stable value of the output current could be achieved only for the short time and soon dropped dramatically and next tuning was needed. Note that special attention to the ions C^{2+} was based under the reason to commission HILAC in the most hard operational mode in accelerating the ions having the almost same charge-mass ratio

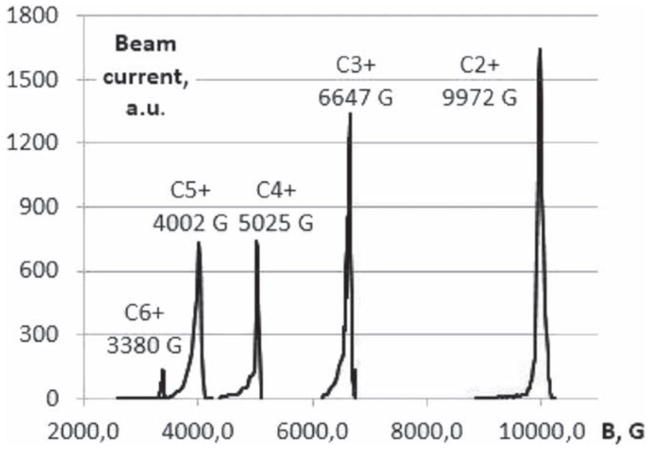

Figure 5. Energy spectra of accelerated carbon ions versus magnetic field in analyzing magnet.

as the ions Au^{31+} have. Accelerated ions C^{5+} и C^{6+} (0.3 mA, 0.15 mA accordingly) were registered at the accelerator output only when sharp focusing of radiation on the target was provided. For registration of a relatively stable C^{5+} beam it was necessary to change the operating spot of the target after every 3–5 pulses, and for the beam C^{6+} - after every pulse. The energy spectrum of the particles was measured with the analyzing magnet (figure 4). To increase the energy resolution two diaphragms with slits before the entrance to the magnet and in front of the Faraday cup were installed. The measured energy of accelerated carbon ions was in good agreement with the design value of 3.2 MeV/u. The amplitudes of the signals from the Faraday cup (figure 5) reflected the fact that the intensity of the accelerated beams C^{6+} were significantly lower than the beam intensities of the other carbon charged states (figure 5).

3. Fixing and solving the problem of beam instability

An ordinary way to increase the intensity of the beams of carbon nuclei in these conditions seemed to increase the density of the laser radiation flux on the target by increasing the energy in the pulse. However, the increasing of the pumping level led to the opposite effect, and the intensity of the beams at the output of the accelerator on average significantly decreased and became unstable, especially for C^{5+} и C^{6+}. On the inspection of the laser, damage of the rear mirror was found. This fact led to an assumption that there was reflected radiation caused such destruction. To fix the problem and to find a way to solve it, the bench tests on the irradiation of carbon, magnesium and iron targets were done. The output radiation of the laser was registered by ultrafast photo detector after reflection from a thin glass plate located on the target-laser path (figure 6). To avoid uncontrolled laser emission caused by the reflection and find the position of non-shifted signal from photo detector the absorber was placed before the focusing lens. Then the irradiation of the targets was done and it was found that if a certain threshold value of the flux density at the target was exceeded, the radiation pulse at the laser output appeared earlier (figure 6). Moreover, for

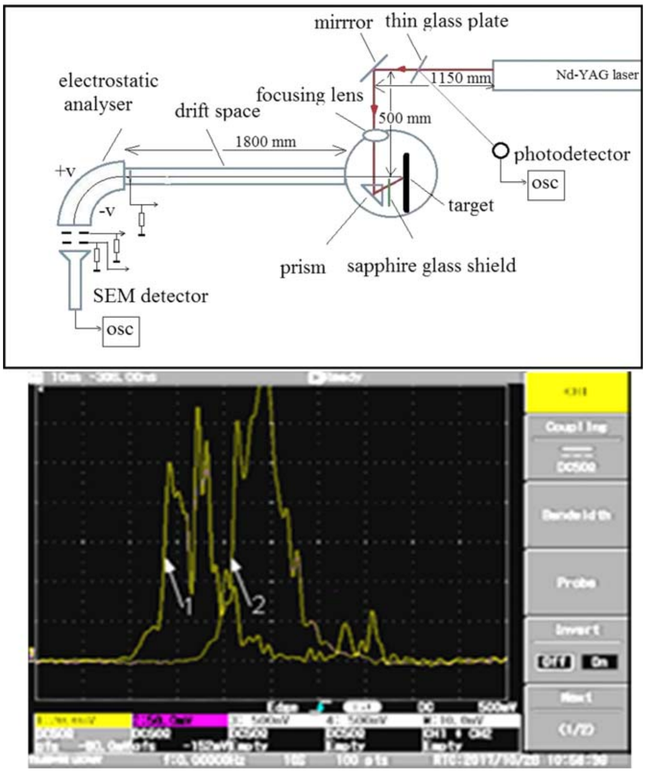

Figure 6. Laser test bench layout for fixing the problem of instability of ion generation (up). Placed in one picture two photo detector signals (10 ns/div); shifted signal (1) was registered when the laser radiation was focused on the target and its time position matched to the low SEM signals and low yield of ions; non-shifted signal (2) was registered when the laser radiation was stopped by the absorber placed before focusing lens, its time position matched to the high yield of ions if the absorber was out (down).

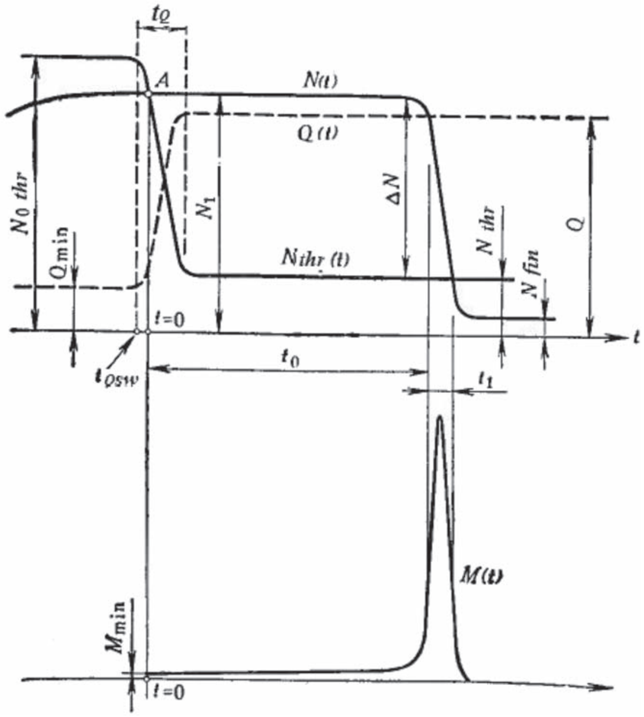

Figure 7. N(t) - inverse population density, N_{thr}(t) - threshold inverse population density, Q(t)- quality factor, t_Q- Q-switching time (up); M(t) - output radiation density (down).

the selected targets these thresholds tuned with the pumping level of the laser setup (or the energy in pulse) were different for the used targets: ~0.6 J/pulse for the magnesium target, ~0.7 J/pulse for the ferrum target and ~0.85 J/pulse for the carbon target. The observed advance in time appearance of the radiation pulse respectively to the non-shifted one varied in 10–20 ns range, as the result of it the flux density on the target and respective to it registered by SEM-detector yield of the ions dropped sharply. Figure 6 presents shifted and 'normal' signals put manually for the clarity in one picture.

Correlating the value of the threshold and the target material led to the assumption that delayed emission could be caused by the radiation of the initial linear part of the giant pulse having duration of about $t_0 = 50$ ns that appeared in advance [13–16] (figure 7), then focused on the target and reflected backward from the produced plasma, causing the uncontrolled emission.

In order to prevent uncontrolled laser emission caused by the reflected radiation, it was tried to place on its path a saturable absorber based on YAG-Cr^{4+} crystal. To find the optimal location for the absorber the experiments at the test bench (figure 6) had been done under the criterions to avoid uncontrolled emission and minimize attenuation of the output laser radiation. Two crystals of different diameters and thickness and different initial transmissions 23% and 13% were purchased and first one then another were placed in three positions of laser setup: behind oscillator and behind each of both amplifiers. The pumping level of the laser setup was tuned so that the output energy without crystals would be 0.41 J. It was found that the placement of each absorber in every position mentioned above led to disappearance of uncontrolled emission even when the pumping was raised up to its highest level. The measured energy of pulsed radiation registered with the calibrated pulsed energy meter placed at the laser output are presented in table 2. Based on these results the optimal place for YAG-Cr^{4+} crystal was chosen in position between two laser's amplifiers (figure 8).

The result of such renovation was that time shifts of the output radiation pulses no longer took place and evolution of ion charge states could be investigated at the maximum flux density on the target (figures 9, 10). The Fe^{17+} presence and traces of Fe^{18+} were observed after first radiation shot on the ferrum target. The carbon nuclei were confidently registered in first ten shots. The cost of such implantation into laser setup of the absorbers having 23% or 13% initial transmission was drop of output energy 20% or 23% respectively.

4. Summary

Injectors of NICA accelerator facility are based on linear accelerators. The Heavy Ion Linear accelerator HILAC has been successfully commissioned using the ion beams from the laser ion source. The ions C^{2+} accelerated to the designed energy value of 3.2 MeV u^{-1} have almost the same charge-

Table 2. Output energy without absorbers was 0.41 J.

Position inside laser setup	Energy, J (YAG-Cr^{4+} 23%, Ø 9,5 мм, 4.15 mm thickness)	Energy, J (YAG-Cr^{4+} 13%, Ø 20 мм, 5.0 mm thickness)
behind oscillator	0.3	0.28
behind first amplifier	0.33	0.317
behind second amplifier	—	0.26

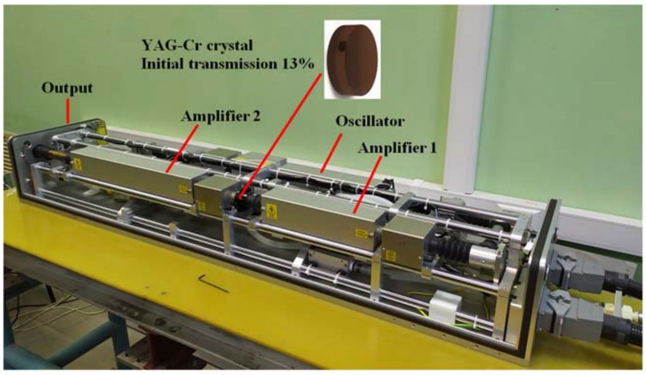

Figure 8. The placement of YAG-Cr^{4+} with initial transmission 13% crystal inside laser setup between two amplifiers leads to 23% decrease in output energy.

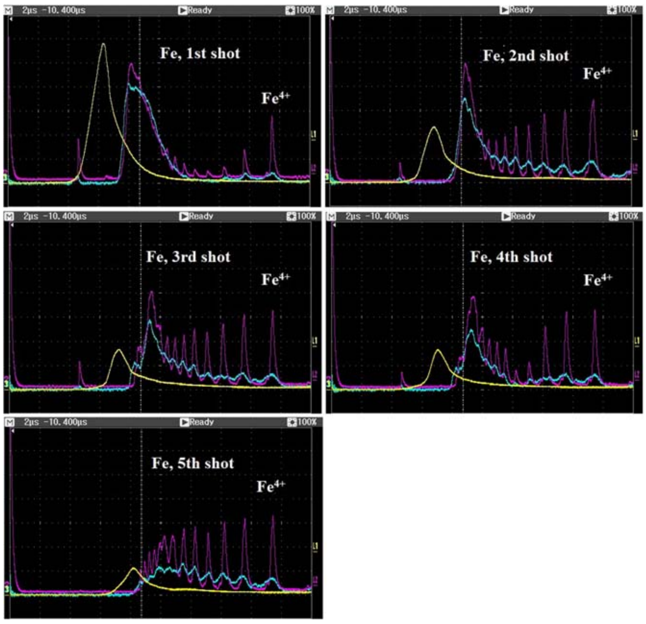

Figure 9. Fe ions charge states shot by shot evolution, lilac - SEM detector signals, blue - collected signal at the SEM input, yellow - collected signal at the analyzer input, white vertical line is TOF marker for Fe^{16+}.

mass ratio as the target ions Au^{31+}. The light ion linear accelerator LILAC is under construction and will be commissioned with the beams from LIS also. In the experiments on colliding the beams of polarized deuterons and light nuclei, a simultaneous operation of both injectors is planned. The beams of light ions from a laser source will be accelerated and injected into the booster by heavy ion injector. The

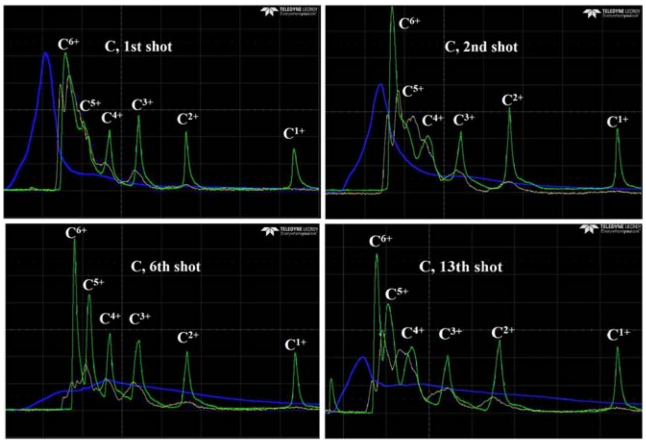

Figure 10. Carbon ions charge states shot by shot evolution (2us/div), green - SEM detector signals, yellow - collected signal at the SEM input, blue - collected signal at the analyzer input.

instability of the beam from the laser ion source was excluded by placement saturable between two laser's amplifiers inside laser setup.

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