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ACCELERATION THE BEAMS OF He^{+} AND Fe^{14+} IONS BY HILAC AND ITS INJECTION INTO NICA BOOSTER IN ITS SECOND RUN

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Abstract

Injector of NICA accelerating facility based on the Heavy Ion Linear Accelerator (HILAC) is aimed to inject the heavy ions having atomic number A≈200 and ratio $A/Z \leq 6.25$ produced by ESIS ion source accelerated up to the 3.2 MeV for the injection into superconducting synchrotron (SC) Booster. The project output energy of HILAC was verified on commissioning in 2018 using the beams of carbon ions produced with the Laser Ion Source and having ratio A/Z=6 that is close to the project one. Beams of He^{1+} ions were injected into Booster in its first run and accelerated in 2020. In 2021 ions of Fe^{14+} produced with the LIS were injected and accelerated up to 200 MeV/u. Beam formation of Fe ions and perspectives of using LIS for the production the ions with high atomic mass A and ratio A/Z matching to HILAC input parameters are described.

HEAVY ION LINEAR INJECTOR

Heavy ion injector of the NICA project is based on the heavy ion linear accelerator (HILAC) and aimed to be injector of gold ions into SC Booster synchrotron of the NICA facility. The main features of it are presented in the Table 1.

Table 1: Main Features of HILAC

	HILAC
Species of ions	Au^{31+}
Z/A	≥ 0.16
Input energy	17 keV/u
Output energy	3.2 MeV/u
Beam current, mA	10
Operating frequency, MHz	100.625
Beam transmission rate, %	98

The accelerator is based on 4-rod RFQ [1] and IH DTL cavities with the KONUS accelerating structure inside [2]. Output energy of the HILAC was verified on its commissioning in 2015-2018 [3,4]. The beams of carbon ions C^{2+} having mass-to-charge ratio A/Z=6 that was close to the project value 6.25 were accelerated. Transverse strong focusing featured for KONUS was provided by two doublets and two triplets. RF power supply system is based on the solid state amplifiers: 140 kW for RFQ, two 340 kW amplifiers for IH1 and IH2 and two 4 kW for rebuncher and debuncher.

LLRF system designed and commissioned in collaboration with ITEP [2] provided five continuous sin input signals for RF amplifiers up to 1V amplitude. Output RF power of the amplifier is tuned by the amplitude of the input signals. Phase shifting between LLRF signals is tuned with accuracy 0.1˚. Level of RF power inside each cavity was controlled by the pickups signals monitoring.

HELIUM ION SOURCE

The beams of He^{+} ions produced with the ion source developed in LHEP JINR were used for the first run of SC synchrotron Booster. For designing helium ion source the proton ion sources described in [3,4] were taken as a prototype. Ion source with cold magnetron cathode and magnetic plasma compression produced ~90% of He^{+} ions (see Fig. 1). There are three basic space emay be attributed to plasma generator: space of auxiliary discharge between magnetron cathode and magnetron anode, space of the basic discharge between magnetron cathode and anode, and area of plasma expansion.

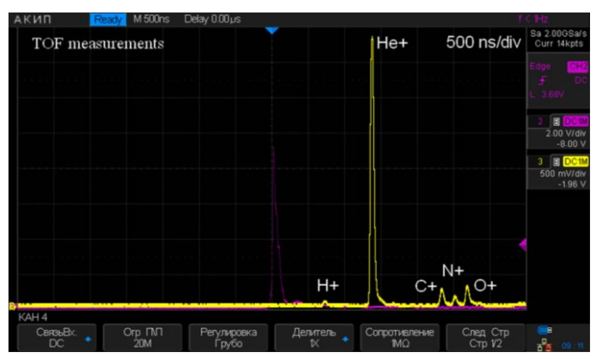

Figure 1: TOF spectrum of the ions at the output of the helium ion source.

LASER ION SOURCE

Laser ion source, developed as the ion source for Alvarez linac LU-20 at the JINR Laboratory of High energy physics in 1983, is based on a CO_2 laser operating in Q-fixed mode. The radiation flux density at the target is estimated as ~10^{10} W/cm² and is enough to produce light ions having mass-to-charge ratio $A/Z \leq 3$ that is the limit value for the acceleration in LU-20. Range of accelerated ions provided with LIS is various enough: $^{6}Li^{3+}$, $^{7}Li^{3+}$,

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B^{4+}, C^{4+}, N^{5+}, O^{6+}, F^{7+}, Mg^{8+}, Si^{11+}. Because of degradation of RF system and problem of RF breakdowns inside LU-20 cavity a necessity was growing up to reduce A/Z ratio of the ions being injected into accelerator. Direct way to do it was to increase flux density of the focused laser radiation on the surface of the target material in order to rise up the number if the ions in higher charge state. For this purpose, CO_2 laser was replaced with the Nd-YAG laser having pulsed energy 1.0 J and pulse duration 10 ns. The expected laser radiation flux density at the target was estimated ~10^{13} W/cm² [5]. Carbon ions C^{5+} produced with the upgraded laser ion source were successfully injected and accelerated in SC synchrotron Nuclotron in accelerating run with satisfied intensity taking extra work of LU-20 RF system and breakdown troubles off. Beams of C^{6+} ions also passed through injection chain successfully but were unstable for application.

Commissioning of heavy ions injector based on HILAC [6,7] opened possibility of acceleration the ions having mass-to-charge ratio A/Z≤ 6.25 at the atomic mass value A high enough. Test bench researches of the laser plasma produced with the Nd-YAG laser were done to find out the high charge states of the carbon and ferrum ions. Presence of C^{6+} and Fe^{16+} ions having almost the same ionization energy 490 eV was observed surely. Moreover, the ions of Fe^{17+} requiring for its appearance ionization energy 1263 eV were observed also (see Fig. 2) [5], so one may expect to accelerate by HILAC the beams of ions having atomic number close to 90.

Beam matching for the RFQ input provided with the LEBT consisting of two focusing electrodes, electrostatic accelerating tube, two short solenoids and XY-steerer.

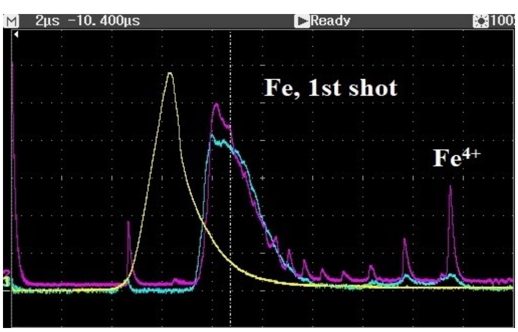

Figure 2: TOF spectrum of the ions at the output of the laser ion source, white vertical line is TOF marker for Fe^{16+}, lilac - SEM detector signals, blue - collected signal at the SEM input, yellow - collected signal at the analyzer input.

ACCELERATION THE BEAMS OF HELIUM AND FERRUM IONS BY HILAC AND INJECTION INTO BOOSTER

For the first run of SC synchrotron Booster the beams of one species He^{+} having mass-to-charge ratio A/Z=4 were accelerated by HILAC up to injection energy 3.2 MeV/u and injected in Booster [8]. The intensity $7{\cdot}10^{10}$ of the ions accumulated in the ring per one pulse of injection and accelerated up to 100 MeV/u was achieved [9]. Beam diagnostic system included four current transformer, three phase probes, beam profile monitors and shoebox pickups (see Fig. 3). Beam transmission was estimated with the current transformers signals placed consequentially behind RFQ, IH2 and behind second bending magnet (see Fig. 3).

The second accelerating run of NICA Booster started from the He^{+} ions acceleration. Ions current duration at the ion source output was 50-60 us. Duration of the ions current at the RFQ input was controlled by HV pulse applied to the focusing electrode used for modulation and tuned in range 1-30 us taking into account that one turn of ions circulation at the injection energy takes ~8 us and three-turn injection is projected. Transmission 50% was observed for 7 mA beam current (see Fig. 4) at the 8 us duration at the RFQ output. Significant beam loading took place in three accelerating cavities of HILAC (see Fig. 5).

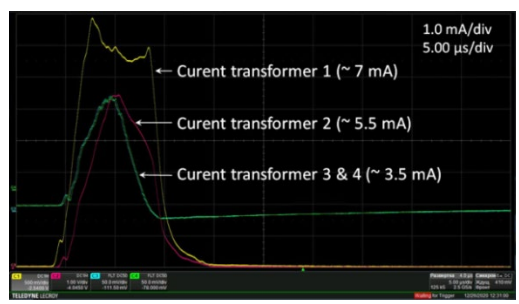

Figure 4: Current transformer signals of He^{+} beam, 7 mA-RFQ output, 5.5 mA-IH2 output, 3.5 mA –behind QT4 triplet.

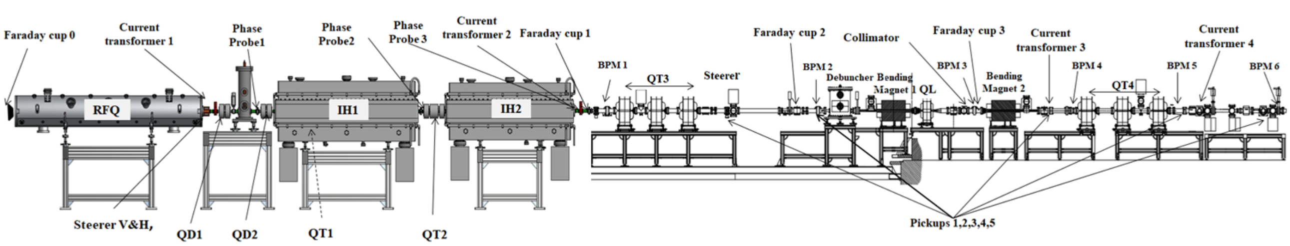

Figure 3: Beam diagnostic units arranged along HILAC.

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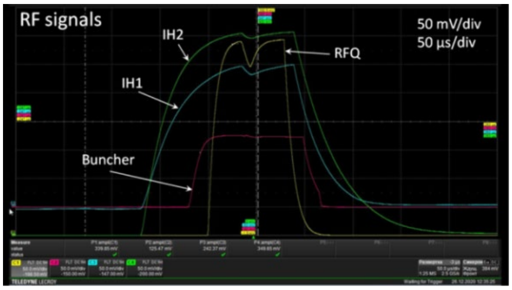

Figure 5: RF beam loading in the HILAC cavities caused with the He^{+} beam.

Beams of He^{+} ions were following by acceleration of Fe^{14+} ions generated with the LIS. On changing ion source HILAC tunings had not been changed because of identical mass-to-charge ratio A/Z=4 both for He^{+} and Fe^{14+} ions. Ions Fe^{14+} current duration ~1-2 us featured for LIS was observed through injection chain and beam transmission was rather less (See Fig.6). No RF loading in HILAC cavities were detected except for a little one in RFQ cavity.

The detected signals of RFQ, IH1 and IH2 pickups (see Figs. 4,5) were observed synchronously to the presented beam currents signals (see Figs. 6,7). One should underline that all run time was spent for the Booster tuning and injector could not been tuned accurately.

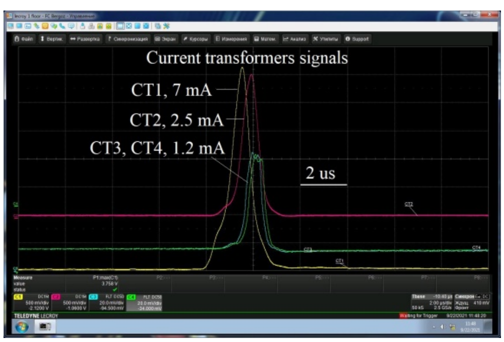

Figure 6: Current transformer signals of Fe^{14+} beam, 7 mA-RFQ output, 2.5 mA-IH2 output,1.5 mA –behind QT4 triplet.

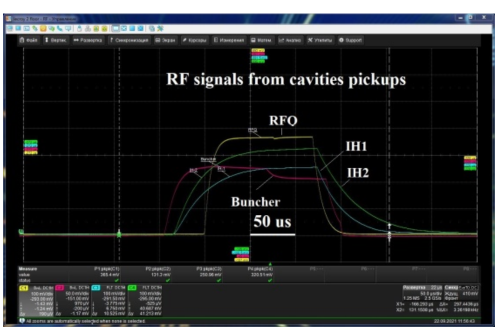

Figure 7: RF beam loading in the HILAC cavities caused with the Fe^{14+} beam.

CONCLUSION

In the second accelerating run of NICA Booster commissioning in September 2021 heavy ion injector based on HILAC injected the beams of ions He^{+} and Fe^{14+} into Booster ring where they were accelerated up to 578 MeV/u. He^{+} ions were provided with the developed helium ion source with cold magnetron cathode and magnetic plasma compression. For the first time the beams of Fe^{14+} ions having mass-to-charge ratio A/Z=4 produced with the LIS could be accelerated and injected in synchrotron ring due to the commissioned heavy ion linear accelerator HILAC. Upgraded LIS based on a Nd-YAG laser in tandem with HILAC make it possible to expect the possibility to generate, accelerate and inject into Booster the ions having atomic number A up to ~90. Searching for the best tuning of heavy ion injector and compensation of beam loading are needed.

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