JOINT INSTITUTE FOR NUCLEAR RESEARCH
Veksler and Baldin laboratory of High Energy Physics

FINAL REPORT ON THE
SUMMER STUDENT PROGRAM

Preparing of LIS to test run of injector HILAC for NICA project and polarized ion source SPIon for injector LU-20. Charge states analysis of LIS.

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Content

Introduction

The new accelerator complex Nuclotron-based Ion Collider fAcility (NICA), is assumed to operate using two injectors: linear accelerator LU-20, as the injector of light ions, polarized protons and deuterons and HILac linear accelerator for heavy ions. For the analysis of the spectrum of the laser source of carbon ions used for HILac accelerator outlet of the accelerating system mounted spectrometer.

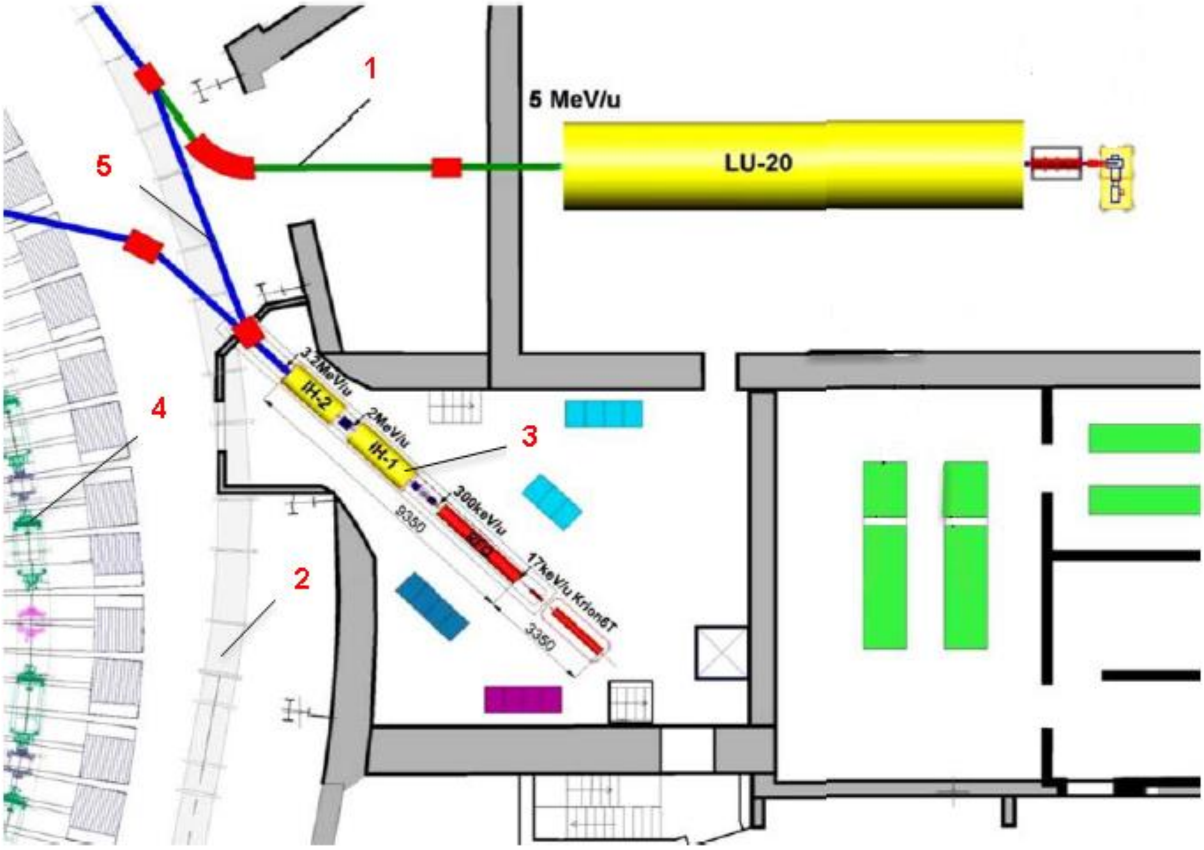


Figure 1. Injection facility: 1 – LU-20 injection; 2 – NUCLOTRON; 3 – HILAC; 4 – Booster ring; 5 – Transport channel.

NICA (Nuclotron-based Ion Collider fAcility)

NICA is a new accelerator complex designed at the Joint Institute for Nuclear Research (Dubna, Russia) to study properties of dense baryonic matter.

After puting the NICA collider into operation JINR scientists will be able to create in the Laboratory a special state of matter in which our Universe stayed shortly after the Big Bang — the Quark-Gluon Plasma (QGP).

The most important research, which will be held on the complex NICA: The most important research, which will be held on the complex NICA [1]:

- The nature and properties of strong interactions between elementary constituents of the Standard Model of particle physics - quarks and gluons
- The search for signs of the phase transition between hadronic matter and QGP; search for new phases of baryonic matter
- Study of basic properties of the strong interaction vacuum and QCD symmetries

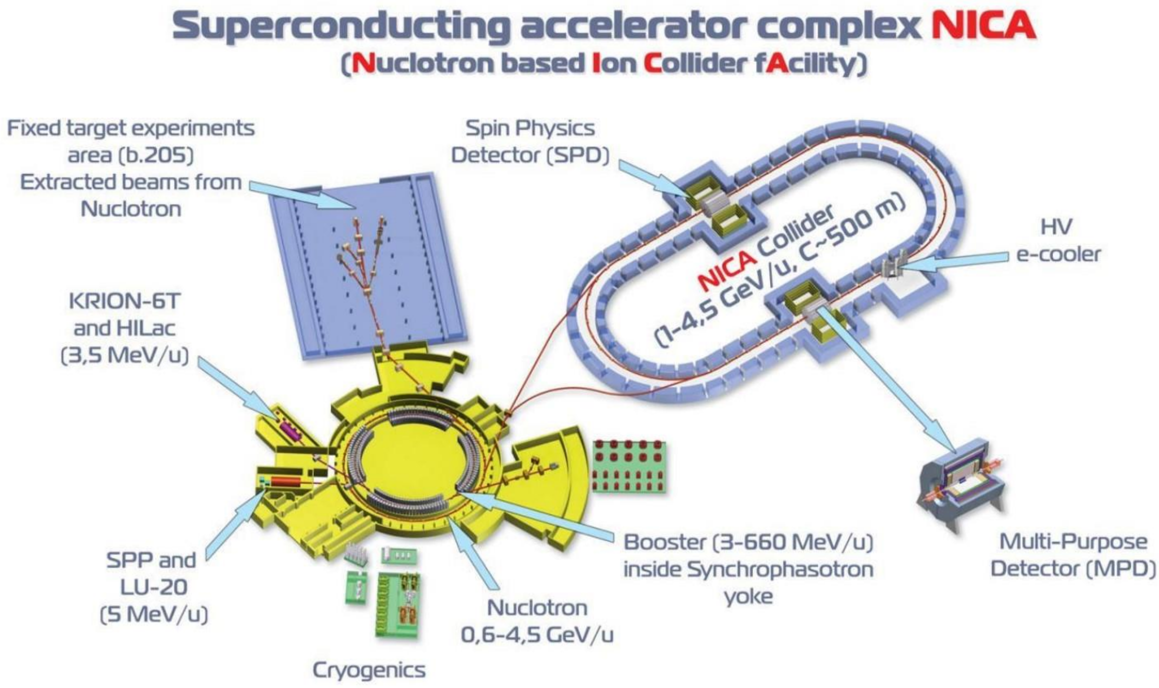


Figure 2. NICA Project

Start of the construction project NICA: 2013. Planned completion: 2020

Heavy Ion Linac (HILac)

HILac it is a HILac consists of three accelerating sections (RFQ and two DTL sections based on IH cavities) and medium energy beam transport (MEBT) [2]. The HILac RF system includes transistor amplifiers and LLRF providing a joint consistent work of all cavities. The cavities for the NICA injector operate at 100.625 MHz. Besides a 3.16 m long 4-Rod-RFQ there are two Interdigital H – type cavities (IH) with 2.42 m and 2.15 m outer length, respectively. The final energies are 300 keV/u for the RFQ and

3.2 MeV/u for the IH-DTL. For the design A/q – value of 6.5 the sum voltage gain is 20.8 MV. The transverse beam focusing along the linac will be provided by two quadrupole doublets as well as by two quadrupole triplets.

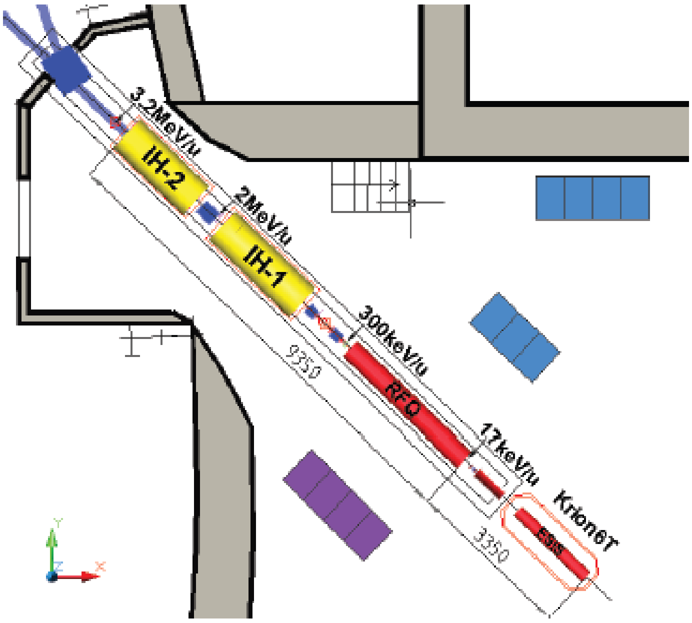
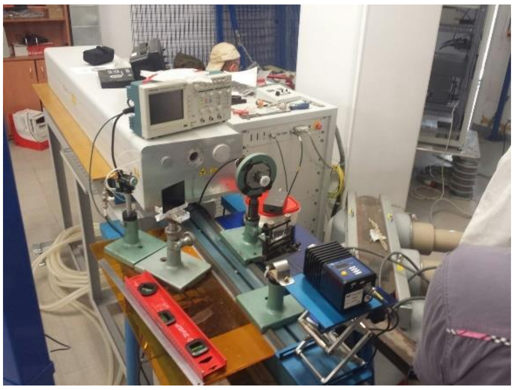


Figure 3. HILAC and its components

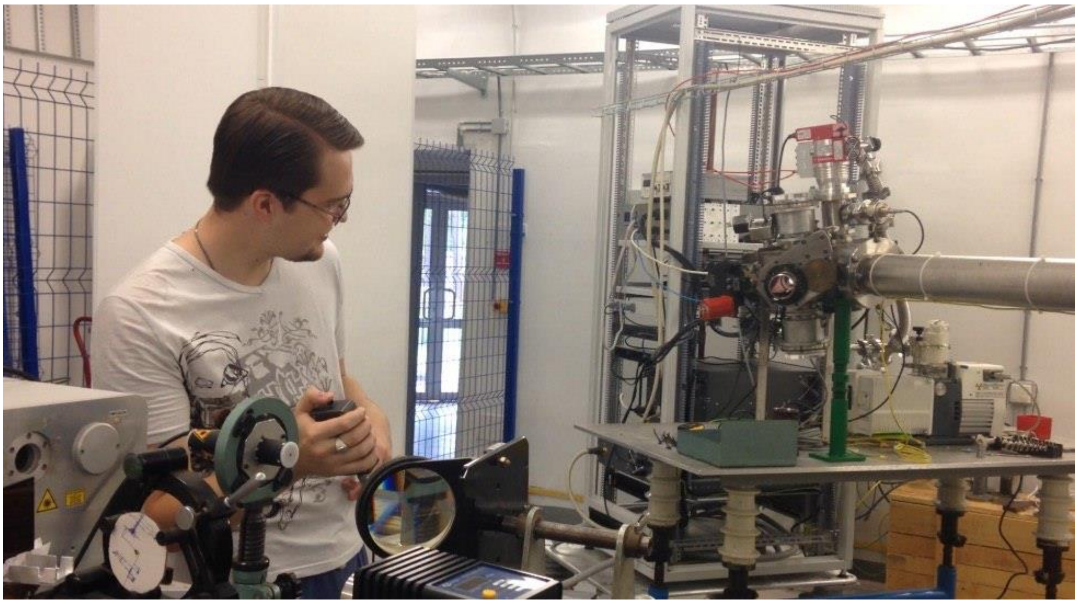
The injector complex Hilac is a laser source. After installation laser source of the work took place on its setting on the target. At the time of assembly (without tanks IH-1 and IH-2) accelerator complex is of interest to consider the resulting ion beam. To analyze the obtained beam at the exit of the accelerator was installed solenoid and a spectrum analyzer. The magnetic field deflects the beam and with an oscilloscope, you can remove the dependence of the current of the electromagnet coils of the voltage at the analyzer commutator.

Configuring laser source

a) Setting the laser power



b) Setting radiation focusing



The laser power and the focus of its radiation is chosen as follows to test RFQ to accelerate ions c ratio of charge to mass number $\frac{Z}{A} = \frac{1}{3}; \frac{1}{4}$. Defocusing of laser radiation on the target can increase the time of production of ions.

c) Calculation of current analyzing magnet for non-accelerated and accelerated beams

A length measuring part transporting channel placed in the electromagnet. Since this calculation is only an estimate, the obtained value was taken as the length of the arc described by the accelerated ions in a magnetic field, and it was l = 0,58 m. The error of its measurement was taken as Δl = 0,1 m.

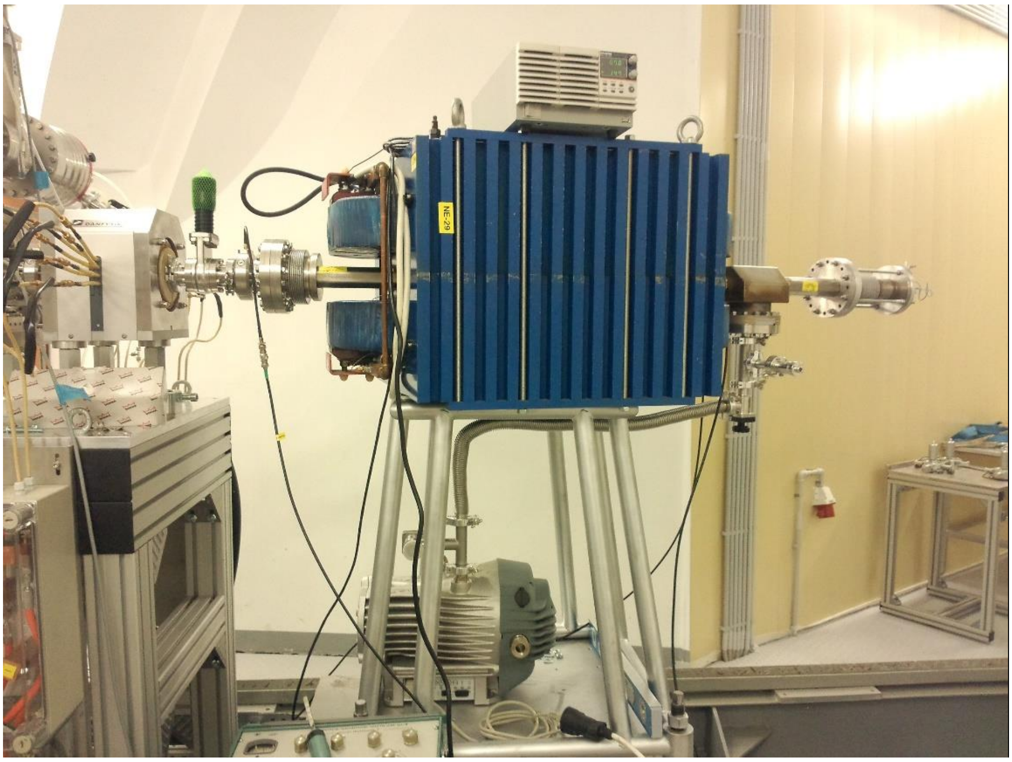


Figure 4. Magnet of the analyzer

According to the obtained value was defined radius of curvature of the trajectory of accelerated ions in a magnetic field, and on it in turn and the required value of the magnetic induction. According to the values of the magnetic field in the magnet, the currents in the coils are determined for each charge of the ions. Calculation results are shown in the tables below (Table 1 and 2).

Table 1. The dependence of the magnetic currents of the collector voltage (acceleration voltage E_1 = 52 keV)

E_1 = 52 keV					
Z	**B, T**	**ΔB, T**	**I, A**	**ΔI, A**	**ΔI/I**
1	0,0856	0,0148	28,23774	4,868576	0,172414
2	0,0605	0,0104	19,9671	3,442603	0,172414
3	0,0494	0,0085	16,30307	2,810874	0,172414
4	0,0428	0,0074	14,11887	2,434288	0,172414
5	0,0383	0,0066	12,6283	2,177293	0,172414
6	0,0349	0,0060	11,52801	1,987588	0,172414

Table 2. The dependence of the magnetic currents of the collector voltage (acceleration voltage E_2 = 300 keV)

E_2 = 300 keV					
Z	**B, T**	**ΔB, T**	**I, A**	**ΔI, A**	**ΔI/I**
1	0,7148	0,1232	235,9184	40,67558	0,172414
2	0,3574	0,0616	117,9592	20,33779	0,172414
3	0,2383	0,0411	78,63946	13,55853	0,172414
4	0,1787	0,0308	58,97959	10,1689	0,172414
5	0,1430	0,0246	47,18368	8,135116	0,172414
6	0,1191	0,0205	39,31973	6,779264	0,172414

d) Preparation and analysis of experimental data

The calculations listed above were taken as basis for further experiments, namely test runs of LIS with RFQ enabled. Schematic layout of the experiment is presented on Figure 5. As presented, the first channel of the oscilloscope was connected to the integrator, which accumulated ion beam current from the output of the magnetic analyzer. The second channel had been used to control RF signal in the RFQ module

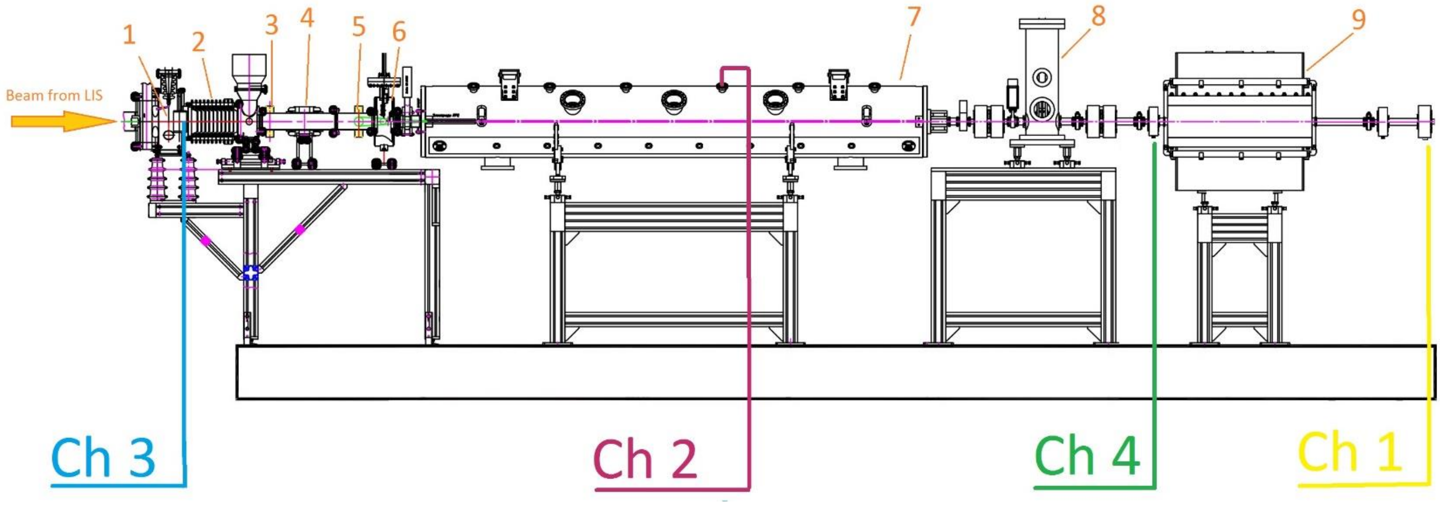


Figure 5. Schematic layout of the experiment: 1 – Electrostatic lenses (E1 and E2); 2 – Electrostatic pre-accelerator; 3 – Magnetic lens L1; 4 – Corrector; 5 – Magnetic lens L2; 6 – Faraday cup; 7 – RFQ module; 8 – Buncher; 9 – Magnetic analyzer;

and to synchronize it with the beam transition. The third and the fourth channels were used to control the input voltage of the electrostatic accelerator (in order to synchronize beam extraction with RF field in the RFQ module) and to control beam intensity at the entrance of the magnetic analyzer respectively.

Firstly, consider the non-accelerated beam at RFK module disabled in order to be convinced of the possibility of obtaining the necessary ion charge using a laser source.

Table 3. The setting values of the acceleration complex for a carbon target.

Settings	**for carbon**
L optics, mm	12
Laser, delay/amp	9/4
U laser, J	1.5
Vertical dual corrector, A	1.3
Horizontal dual corrector, A	0.3
High voltage source 60, kV	32.8
High voltage source 120, kV	9.3
L1, V	0
L2, V	0
High voltage source, kV	51
Amplifier RFQ, W	0
RF peak to peak, V	0
Angle of inclination of the pipe, grad	20
Current of magnet, A	different

For accelerating voltage of 51 kV is obtained dependent on the availability of signal on analyzer from the value of the magnet current (Figure 6).

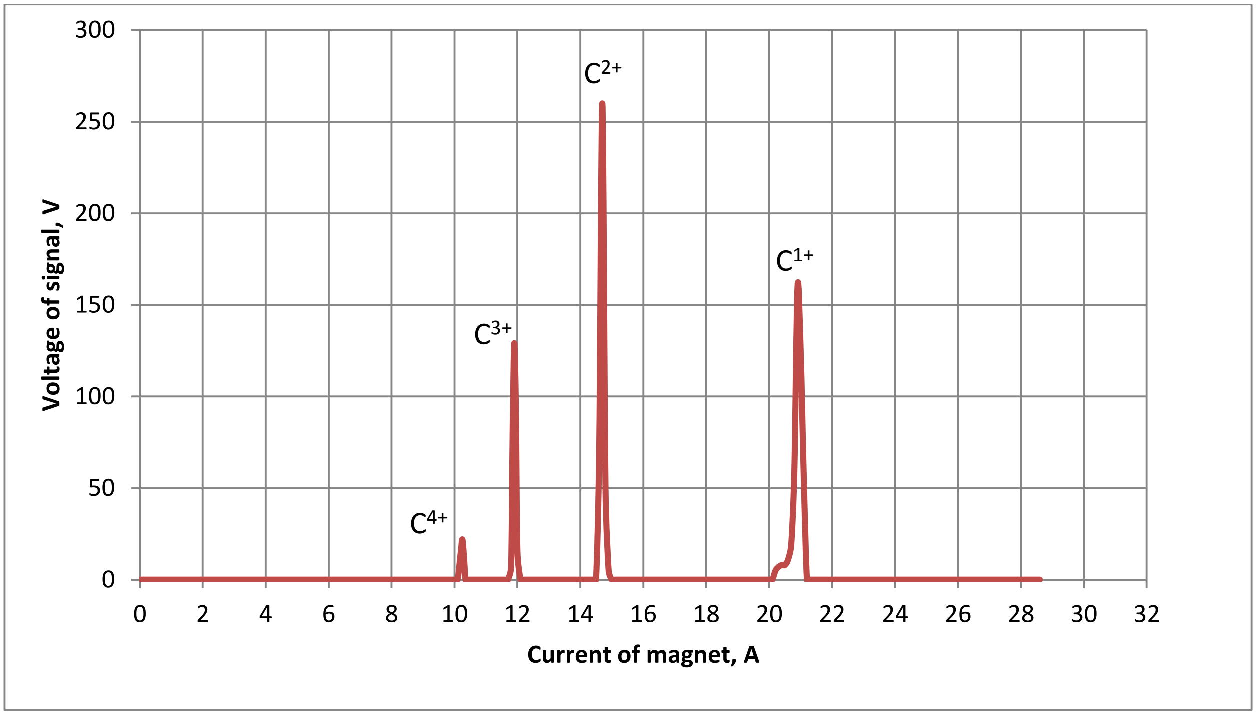


Figure 6. The spectrum of carbon (E_1 = 51 keV)

Results in the beam acceleration with RFQ module are also obtained. Parameters accelerator complex for which the data obtained are presented in the results table 4. The RFQ module usage required special parameters of the whole system.

Table 4. The setting values of the acceleration complex for a carbon target.

Settings	**for carbon**
L optics, mm	12
Laser, delay/amp	9/4
U laser, J	1.5
Vertical dual corrector, A	1.1
Horizontal dual corrector, A	0.3
High voltage source 60, kV	27.1
High voltage source 120, kV	24.1
L1, V	300
L2, V	600
High voltage source, kV	68
Amplifier RFQ, kW	33
RF peak to peak, V	0,542 (40 dB)
$Slit_2$: U_{lock}, V	-400
Angle of inclination of the pipe, grad	20
Current of magnet, A	different

As the result, we have obtained stable 230 mkA signal from input slit of the analyzer (Figure 7, channel 4) and 3,7 V signal from the output integrator of the analyzer (Figure 7, channel 1).

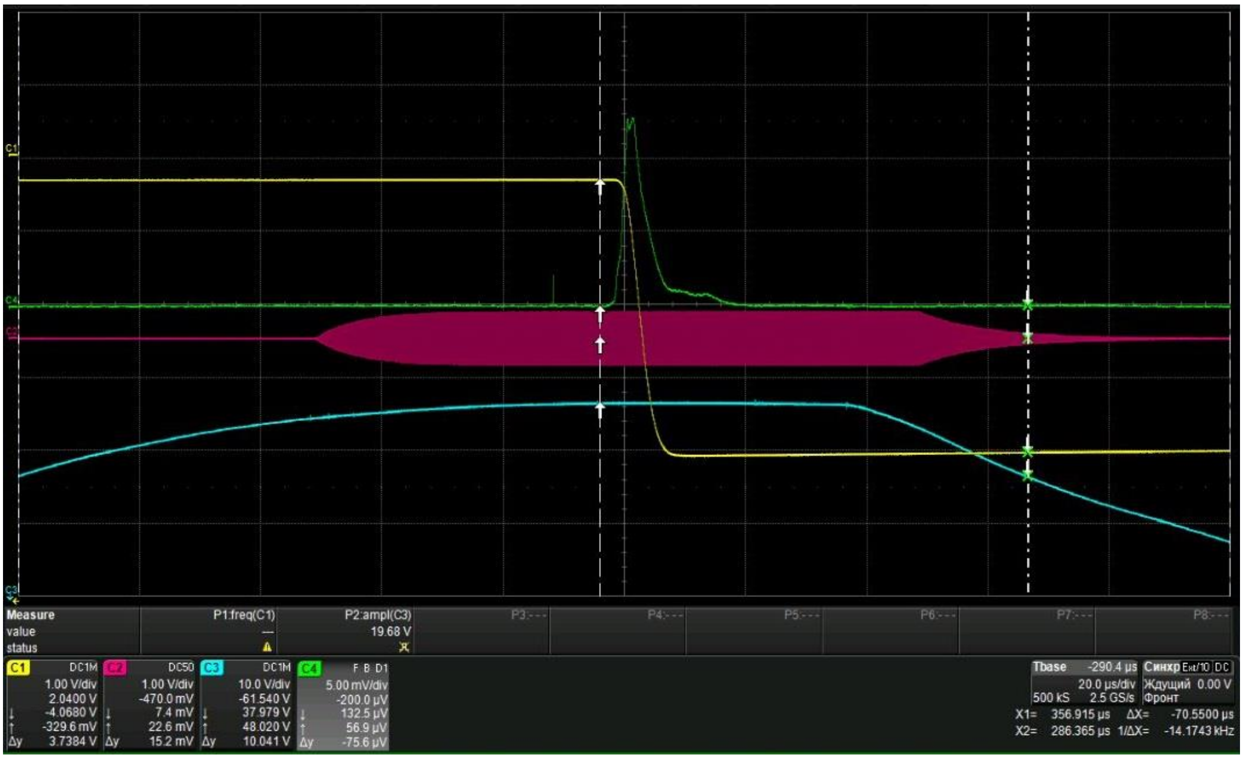


Figure 7. Experimental oscillogram

The spectrum of carbon charge states 3 and 4 is shown in Figure 8.

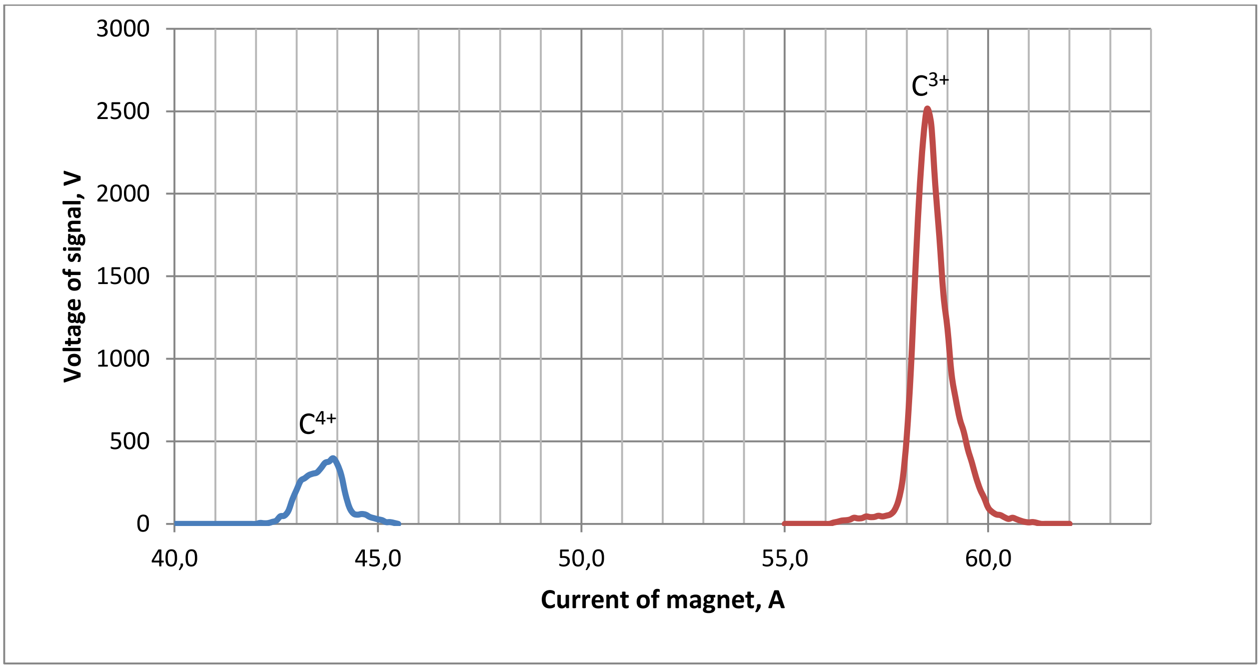


Figure 8. The spectrum of carbon (E_2 = 300 keV)

Conclusion

The resulting calculations values of current coincide with values within the error limits for which the signal is observed in the ion acceleration experiment with RFQ enabled and with disabled RFQ.

Familiarization with source of polarized ions (SPI) facility designed to produce beams of polarized protons and deuterons for Nuclotron/NICA project

The NICA program includes several projects, and experiments with polarized light ion beams are considered to play a significant role in the whole program. Development of the polarization program at NICA facility is aimed on increasing pulsed intensity of polarized nuclei [3].

In order to provide the substantial of pulsed intensity the new SPI project was developed (Source of Polarized Ions project). This project assumes the development of source using the charge-exchange ionizer, which is the substantial part of the equipment from IUCF (Bloomington, USA).

Production of polarized ions in the SPI is divided into several steps (Figure 9). First of all, H_2 molecules go through RF discharge dissociator where them dissociate into atoms. Then, thermal hydrogen (deuterium) atoms are polarized by passage through inhomogeneous magnetic field of sixtupole magnets. After that, nuclear polarization is increased with RF transitions and polarized atoms are converted into polarized ions in the charge-exchange ionizer.

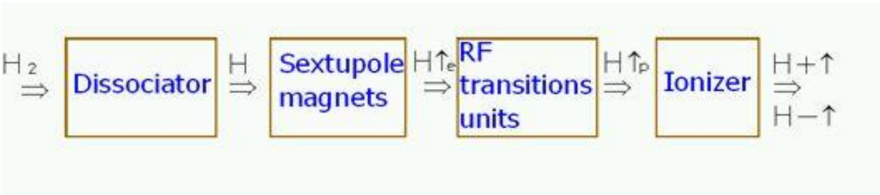


Figure 9. Process of polarized ions production in the SPI

Schematic layout of the SPI source is shown on Figure 10.

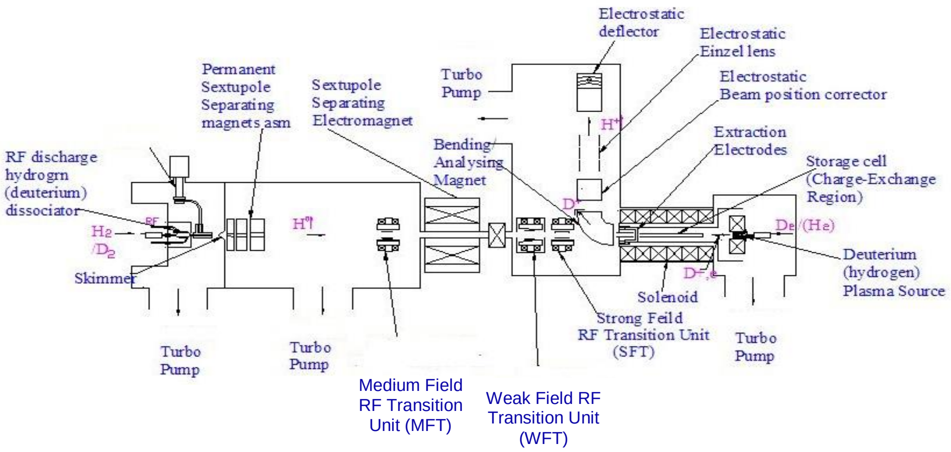


Figure 10. Schematic layout of the SPI source

The SPI source can be divided into two major parts (Figure 11):

1. Hydrogen (deuterium) RF discharge dissociator;
2. SPI Plasma Ionizer;

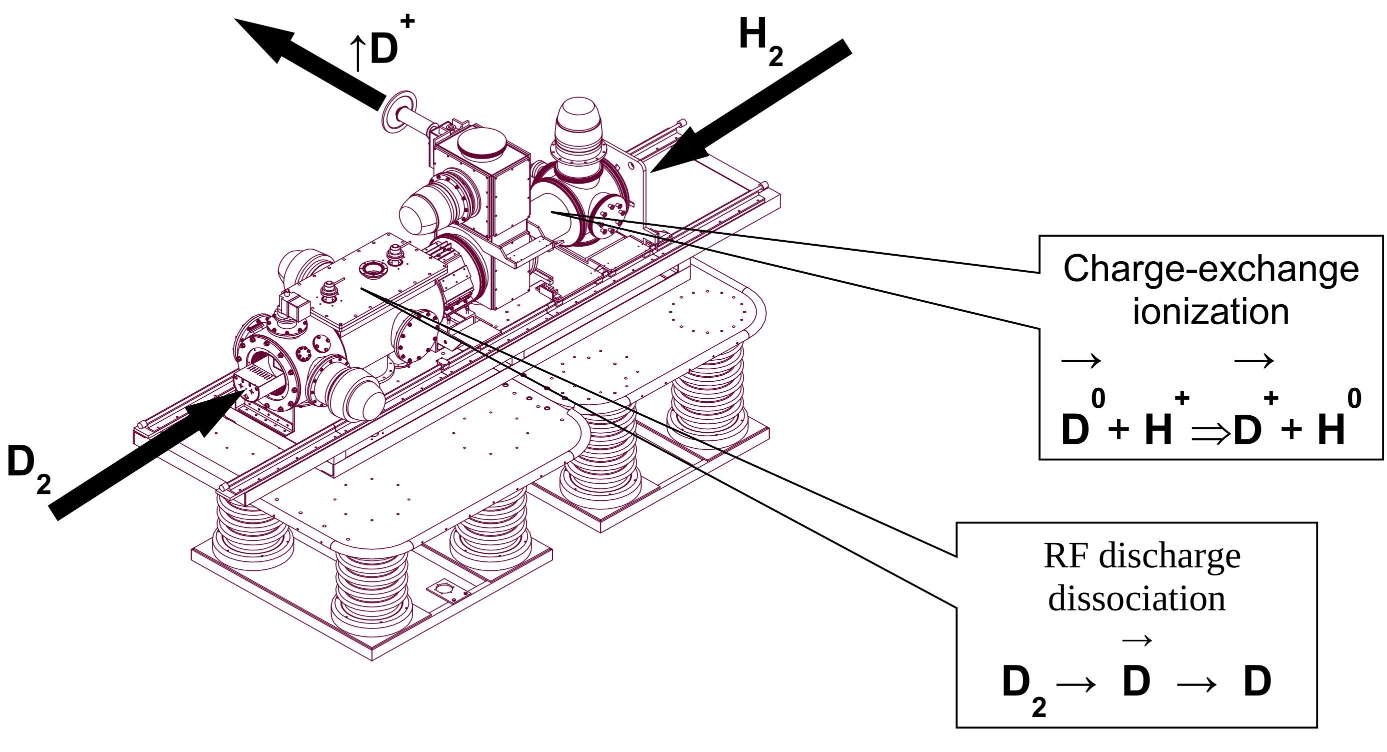


Figure 11. General view of SPI source with specifications of basic processes

Hydrogen RF discharge dissociator (Figure 12) was designed by INR RAS in order to provide 3ms pulsed RF discharge (with 1Hz pulse of RF discharge). It has long cooling channel combined with cryocooler which allows to cool $\mathbf{D^0}$ nuclei down to 80 K.

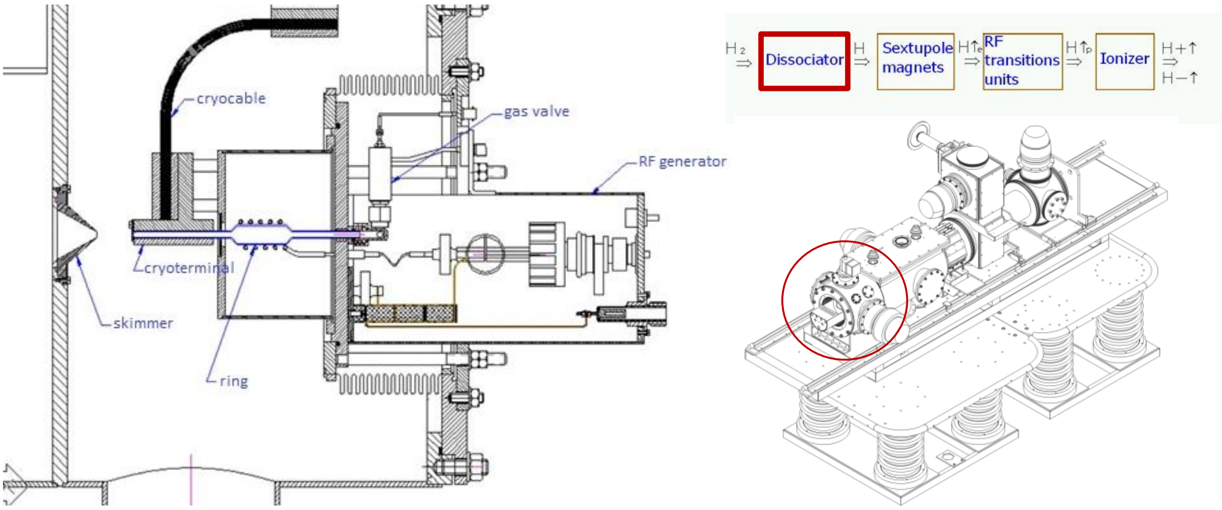


Figure 12. Schematic layout of RF dissociator with specification of its location

After dissociation and cooling nuclei go through skimmer which forms thin bunch, that goes through polarizing permanent **sixtupole magnetic field**. Then, polarized nuclei transit through **analyzing magnet** and RF transition units right to **SPI plasma ionizer** (Figure 13). Ionizer can carry two possible ways of ionization:

1. With free atomic hydrogen beam in the charge-exchange region;
2. With storage cell in the charge – exchange region;

Ionizer efficiency depends on intensity of plasma jet in the charge-exchange region and respective unpolarized ion current extracted from the ionizer. Current experiments are held with free atomic hydrogen beam in the charge-exchange region. Schematic layout of the SPI plasma ionizer and photo of its hydrogen plasma source are shown on Figure 13 and Figure 14 respectively.

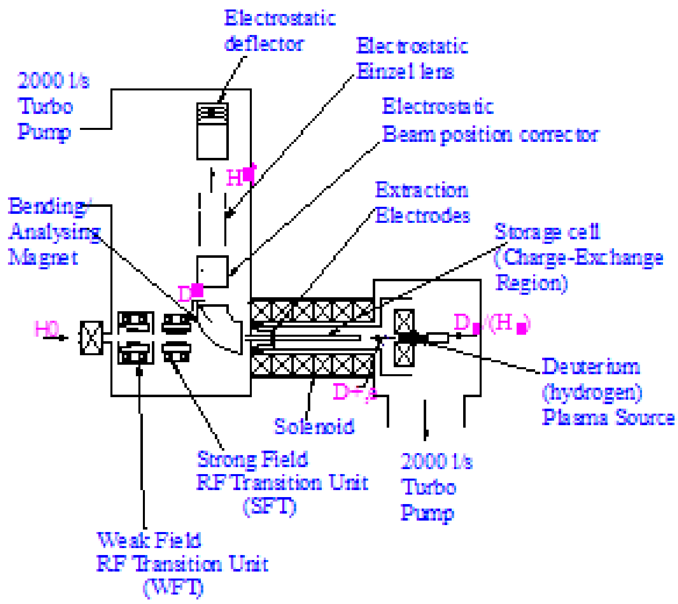


Figure 13. Schematic layout of the SPI plasma ionizer

Figure 14. Hydrogen plasma source

SPI plasma ionizer is based on cold cathode arc-discharge plasma source that provides ~ 200 A, 200μs pulsed discharge current and 6 kV, 10 μs discharge ignition voltage. [4] Ion flux in plasma is in Ampere region and extracted unpolarized ion fluxes proportional to extraction voltage in 3/2 degree: $I_b \propto U^{3/2}$. The SPI ionizer is also equipped with pulsed gas valve that is synchronized with plasma source pulses. In order to provide parameter of pulses listed above, special power supplies were developed and tested in collaboration with INR RAS in 2015 (Figure 15 and Figure 16). Control system of the PS was also developed at INR and JINR (Figure 17).

Mode of operation: 25kV pulse;

Pulse length: 400 μs;

Pulse repetition rate: 1 Hz

Figure 15. Hydrogen plasma source HV pulse generator

Figure 16. High-voltage pulse generator of the arc plasma source

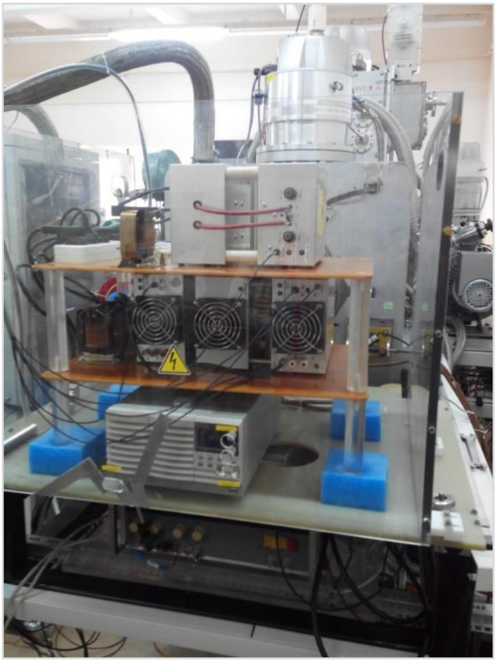


Figure 17. Power supplies for the plasma source

The results of the ionizer tests are presented on Figures 18, 19, 20 and 21. As presented on Figure 13 we have managed to obtain 160 mA pulse ion current (D^+). Duration of obtained signal was about 100 μs (about 35% of duration of the accelerating voltage pulse).

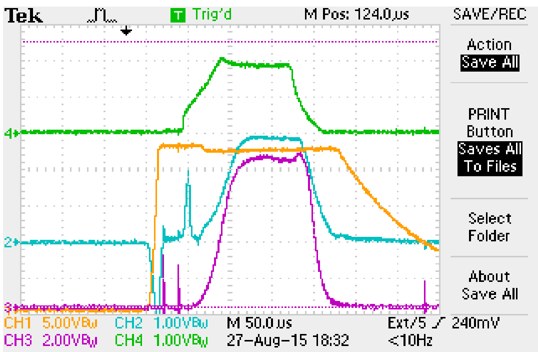


Figure 18. Power supplies for the plasma source

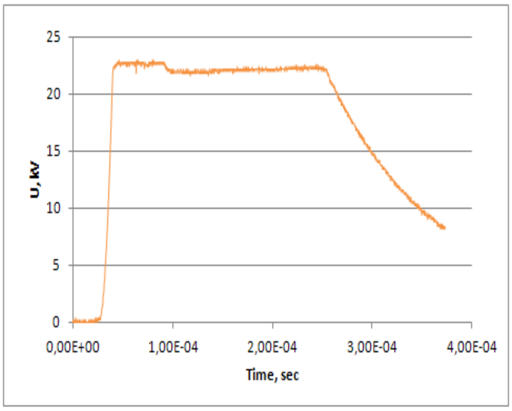


Figure 19. Accelerating voltage pulse: 22kV, 300 µs

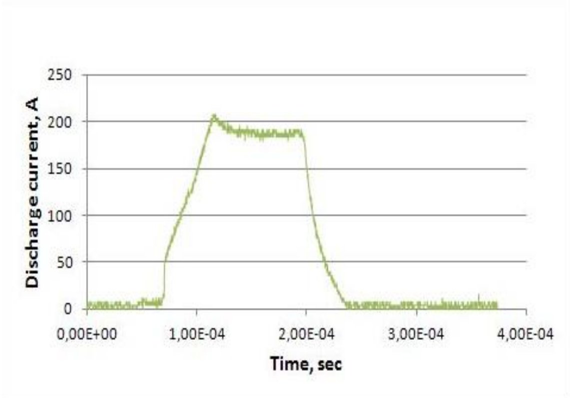


Figure 20. Discharge current pulse of the plasma source, 200 A peak, 100 µs

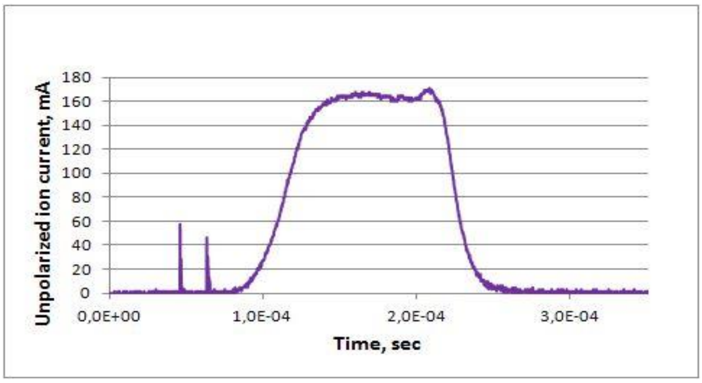


Figure 21. Unpolarized ion current (D+) downstream the analyzing magnet

The SPI-project includes the following stages:

- ✓ Development of the high-intensity **Source of Polarized Ions**;
- ✓ Complete tests of the **SPI**;
- ✓ Modification of the linac pre-accelerator platform & power station (Figures 22 and 23);

Figure 22. High voltage platform

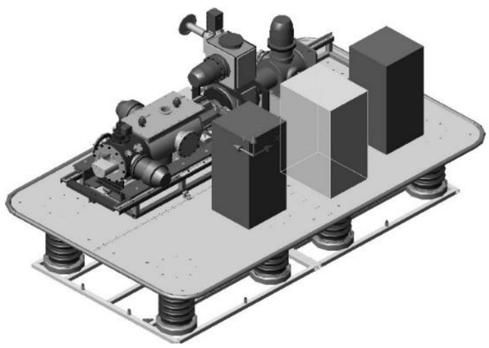


Figure 23. General view of HV

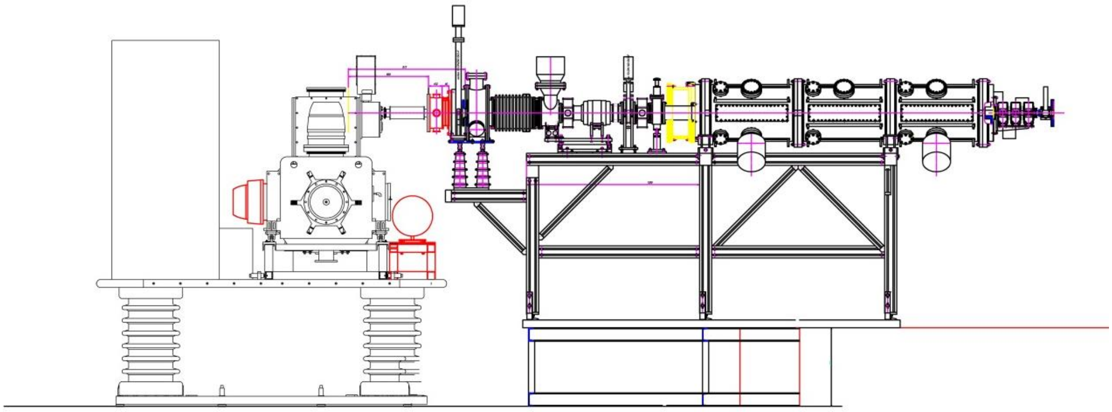


Figure 24. Schematic layout of SPI matched with LEBT and RFQ

- ✓ **SPI** matching with Low Energy Beam Transfer (LEBT), RFQ & linac (Figure 16);
- ✓ remote control system (console of linac) of the **SPI** under the high voltage;
- ✓ **SPI** & **Linac** runs with polarized beam and polarization measurements at the NUCLOTRON;

Conclusions

- SPI is now under tests at the JINR test bench;
- ABS module and plasma ionizer operation has been tested and the results were found satisfactory;
- Polarized proton beam of 1.3-1.4 mA peak has been produced with free atomic beam in the charge-exchange region of the source;
- It is planned to continue tests with the storage cell installed into the ionizer;

Acknowledgement

We would like to express our appreciation to PhD Butenko A.V., our practice supervisors and director of University Centre of Joint Institute for Nuclear Research, S. Z. Pakuliak, for giving us an opportunity to participate in Student Summer Program 2016.

References

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[3] V.V. Fimushkin, et al., "Development of polarized ion source for the JINR accelerator complex", Proceedings of 16th Workshop on High Energy Spin Physics (DSPIN-15)

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