THE NEW OPTION OF FRONT END OF ION LINAC

A. Kovalenko, JINR, Dubna, Russia
A. Kolomiets, ITEP, Moscow, Russia

Abstract

The standard set of elements consisting of RFQ, two tanks of accelerating IH-structures, external matching and focusing sections is modified to achieve better performances. Special insertions corresponding to buncher and quadrupole triplet are combined within the RFQ tank, whereas superconducting focusing elements are install between the DTL - structure tanks. Simulation of the system parameters was performed to provide the output beam energy of 5 MeV/u for the ions with charge – to - mass ratio of $0.33 \leq Z/A \leq 1$. Possible application of the considered scheme for the NICA facility at JINR (Dubna, Russia) is discussed.

INTRODUCTION

The work was motivated by our desire to find optimal way of the constructing linear accelerator chain aimed at injection of light ions and protons for the NICA complex at JINR [1] and also for other applications, in particular for the future carbon/proton superconducting (SC) medical synchrotrons [2].

The physics research program at NICA [3] requests the beams of heavy and light ions, protons, polarized deuterons and protons as well. The facility is based on the existing SC synchrotron - Nuclotron that is in operation since 1993 [4] and that was upgraded in 2008-2010[5]. The accelerator complex will include also two separate injection chains, 25 T·m SC booster synchrotron, the collider SC rings, beam transfer channels. The collider will provide heavy ion collisions of average luminosity of 10^{27}cm^{-2}s^{-1} at the energies of $\sqrt{s_{NN}} \sim (4 – 11)$ GeV. The collider detector MPD is scheduled for starting data taken in 2017. The fixed target experiment Baryonic Matter at Nuclotron (BM@N) is planned to start data taking in 2015 in the beam of gold ions extracted from the Nuclotron. The NICA will provide polarized proton and deuteron collisions up to $\sqrt{s}$ = 26 GeV and 12.5 GeV/u, respectively, with the average luminosity of 10^{31} cm^{-2} s^{-1}.

The two injection chains aimed at heavy ions and protons/light ions (including polarized ones) injection contain respectively the following: high charge state heavy ion source → the new heavy ion linac → SC booster → Nuclotron → collider and the sources of protons, deuterons (including polarized) and light ions → upgraded existing linac LU-20 → Nuclotron → Collider.

The Alvarez type proton linac LU-20 was commissioned in 1974. At the present time LU-20 provides proton beam with energy 20 MeV and light ions ($Z/A \geq 1/3$) up to 5 MeV/u. The LU-20 planned upgrade includes, at the first stage, replacement of old high voltage preinjector by the new one having much lower voltage of the ion source platform (U = 100 kV) and the use of RFQ to provide the ion energy required for injection to LU-20.

It is clear, however, that use of LU-20 for acceleration of ions heavier than protons is not very efficient. Moreover it would be very risky to expect reliable operation of the old linac in the coming decades even in the case of complete and very expensive replacement of the drift tubes containing quadrupoles inside.

The main goal of the work is design of compact and efficient linac that can be considered as an option of light ion injector for NICA project.

LIGHT ION INJECTOR

General Layout

Particles that will be accelerated in this device are protons, deuterons (including polarized) and other ions with charge - to - mass ratio of $1/3 \leq Z/A \leq 1/2$, in particular $^{12}C^{6+}$ and $^{12}C^{4+}$ as well. The specified values of the beam currents and the expected transverse emittance define the choice of the injector layout and basic parameters of its accelerating structures. After analysis of different possibilities, the scheme shown in Figure 1 is proposed.

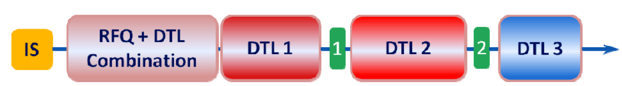

Figure1: Structural scheme of the NICA injector of light and polarized ions. (IS – ion sources)/

Initial part is a combination of RFQ and the DTL that was designed following the idea proposed in [6]. This combination allows to form at output of initial part beam parameters required for injection to DTL 1 and to exclude MEBT with focusing and rf elements for beam matching between RFQ and DTL 1.

DTL 1 and DTL 2 are designed for acceleration of ions with Z/A = 0.33 up to final energy 5 MeV/u. DTL 3 is aimed only for proton acceleration and has to be switched off in the other cases.

Superconducting solenoids are used for beam focusing between DTL sections. It allows reducing drift space between cavities and improving longitudinal beam dynamics. Application of superconducting elements in the proposed new injector is logically follows from the NICA basic technology concept and the advanced level of cryogenics in the Laboratory of High Energy Physics.

RFQ

The RFQ is based on a resonant structure with coupling windows developed in ITEP for TWAC facility injector [7]. The main attention at the design stage was devoted to minimization of the beam longitudinal emittance formed by the RFQ in the case of rather high (> 90%) transmission coefficient. Following to the results obtained in [8], the sinusoidal modulation of the RFQ vanes is used only at the gentle buncher part whereas the trapezoidal one is applied at the main acceleration part with constant modulation coefficient. The trapezoidal modulation provides 15 – 20% higher RFQ accelerating efficiency at the same modulation.

The main feature of the RFQ is the new approach to the beam formation at the RFQ output that provides converging beam in both transverse planes as well as in longitudinal one. It is achieved by adding after regular RFQ vanes several drift tubes connected with opposite vanes with increased distance from axis. Potential difference between tubes is the same as applied to regular vanes.

Drift tube part accelerates ions with higher accelerating efficiency compare with modulated vanes. Due to absence of transverse focusing in this part of structure transverse envelopes amplitude increases approximately by a factor of two. Drift tubes aperture is chosen to exclude the particle losses. Two additional pieces of vanes with quadrupole symmetry $\beta\lambda$ long each are installed after the last gap. The distance between the vane sets is $\beta\lambda$ also. The model of the front end output is shown in Figure. 2.

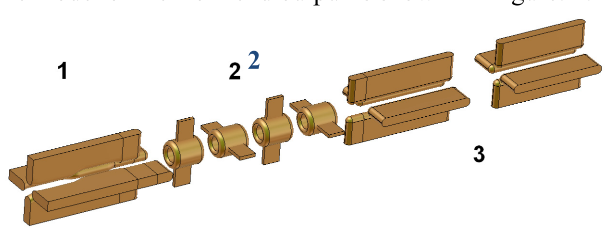

Figure 2: 3D model of the RFQ output part: 1 – the end of regular RFQ vanes, 2 - drift tubes, 3 - rf quadrupoles.

Basic parameters of RFQ + Hybrid combination are given in Table 1.

Table 1: The RFQ Main Design Parameters.

Parameter	Value
Accelerating frequency, MHz	109.0
Voltage between the vanes and tubes, kV	132.0
Average radius, mm	7.50
Thickness of the electrodes, mm	5.25
Maximum modulation coefficient	2.0
Betatron phase advance at the focusing period (minimum), deg.	36
Transverse acceptance (normalized), cm·mrad	0.42
Regular RFQ length, m	3.0
Total combination length, m	3.55
Output beam energy, MeV/u	0.82
Injection energy, MeV/u	0.03
Beam transmission @ I = 10 mA	95%
Maximum electric field at the electrodes surface, kV/cm	227

Hybrid structure consisting of a number of drift tubes without any transverse focusing whereas the focusing is provided by rf quadrupoles placed between the drift tube sections is described in [9]. It is possible to say that described design is a combination of conventional RFQ with a short length hybrid structure. The rf quadrupoles geometry is chosen to provide the bunch enter and exit at the field level closed to zero, i.e. at the accelerating field phase of ±90°. The influence of the output quadrupoles is equivalent to the four static quadrupole lenses forming the FDODF period, i.e. triplet. The distances between the opposite vanes in output quadrupoles are chosen to provide transformation of the beam with quadrupole symmetry at regular RFQ output into converging axially symmetric beam.

Drift Tube Structures

The DTL section is introduced by a crossbar type structure based on the same resonant structure with the coupling windows that has been used for the RFQ. The advantages of such option in compare with the commonly used IH structure are the following: 1) it is possible to equalize gap field level along the section including the first and the last gaps and to exclude dipole component of the field at the system axis and moreover 2) unification of the resonant structures for all cavities leads to lower production and operation cost of the injector. The main design parameters of the DTL sections are presented in Table 2.

Table 2: Design Parameters of DTL Cavities

Parameter	DTL 1	DTL 2	DTL 3
Frequency, MHz	109	109	218
Aperture, mm	10.0	10.0	10.0
Number of acceleration gaps	10	13	11
Electric field at the drift tube surface, kV/cm	230	230	230
Gap length, mm	30.0	50.0	50.0
Gap voltage, kV	600.0	700.0	700.0
Cavity length, mm	830	1605	1200
Output energy, MeV/u	2.58	5.06	10.72

BEAM DYNAMICS SIMULATION

Computer code PreRFQ, ALFIL and TRANSIT, created by the ITEP, were used for the beam dynamics simulation. The first code is aimed for calculations of field distribution in RFQ cell with different types of the vane modulation. ALFIL was used for field calculations in accelerating gap. TRANSIT is the program for multi-particle beam dynamic simulation. The 3D representations of the field are used in TRANSIT for all RFQ cells, accelerating gaps and solenoid. PIC solver is used for calculating particle interactions.

ISBN 978-3-95450-122-9

The transverse envelopes of the beam of $_{12}C^{4+}$ ions at beam current I = 10 mA calculated by the TRANSIT code are shown in Figure 3.

Twiss parameters of transverse emittances at RFQ output are given in Table 4. It shows that the parameters have very small dependence on beam current. It confirms that the proposed modification of RFQ output provides converged beam with axial symmetry that can be directly injected into DTL 1 cavity for wide range of beam current.

Calculated beam transmission in injector is showed in Figure 4. It shows that in design range of beam current $0 < I < 10$ mA it is fully defined by RFQ transmission. Additional particle losses in DTL cavities for higher beam current are explained by increasing phase width of bunch at RFQ output due to space charge.

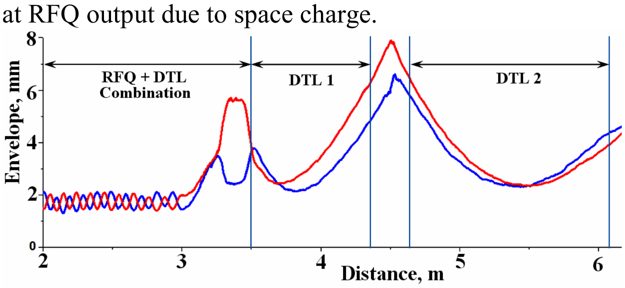

Figure 3: Calculated envelopes of $_{12}C^{4+}$ – ions at 10 mA for x (blue curve) and y (red curve) planes.

Table 3: Twiss Parameters of the Beam at RFQ Output

Beam current, mA	α_x	α_y	β_x m/rad	β_y m/rad
0	-1.82	-1.95	0.468	0.656
5	-2.04	-2.40	0.494	0.767
10	-2.00	-2.63	0.484	0.833
15	-1.96	-2.04	0.477	0.650

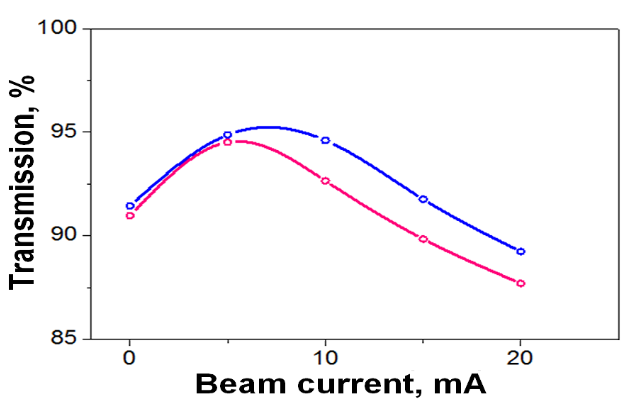

Figure 4: The dependence of $_{12}C^{4+}$ transmission on the beam current. Blue curve represent transmission at RFQ output, red one – at DTL 2 output.

CONCLUSION

Results of development and computer study of light ion injector for NICA project show that proposed combination of RFQ and Hybrid structure provides beam with parameters required for direct injection into following DTL cavity. Beam parameters have only slight dependence on beam current. This approach allows designing injector front end without use of MEBT with additional focusing and rf elements. It can be useful option for design heavy ion linac.

Computer simulations showed that RFQ and DTL cavities can be built using the same type of resonant structure – four vane with coupling windows that reduces manufacture and operation cost of injector.

Injector with total length $L_{tot} = 6$ m accelerates ions with Z/A = 0.33 up to energy W = 5 MeV/u. Accelerating structures are designed for conservative surface field $E_s \leq 230$ kV/cm to guarantee reliable operation. Injector has only two additional short DTL cavities comparing with structure required for upgrade of LU-20. Nevertheless injector provides higher beam parameters and more efficient and reliable operation. With adding short DTL cavities designed for acceleration of proton injector can completely replace old LU-20 linac for NICA project.

The proposed and considered design is adequate also to carbon ion and proton injector of the future medical synchrotrons.

REFERENCES

[1] Nuclotron-based ion collider facility NICA at JINR, http://nica.jinr.ru/.

[2] A.Kovalenko, N.Agapov et al. “Superconducting Magnet Technologies as basis for Design of Medical Carbon and Proton Synchrotron at Dubna”, Workshop “Physics for Health in Europe”, CERN, February 2-4, 2010. http://cern.ch/physics-for-health

[3] V.Kekelidze et al. Physics Program at NICA@JINR. 35th Int. Conf. on High Energy Physics (ICHEP2010), Paris, France, July 22-28, 2010.

[4] A.D.Kovalenko, “Status of the Nuclotron”, EPAC94, London, June 1994, Proc.v.1, pp.161-164, (1995).

[5] A.Eliseev, N.Agapov et al. “Results of the Nuclotron Upgrade Program”. Proc. IPAC’2011, September 4-11, 2011, San Sebastian, Spain, paper WEPS013.

[6] A. Bechtold, U.Bartz, M. Heilmann, P. Kolb, H. Liebermann, D. Mader, O. Meusel, H. Podlech, U. Ratzinger A. Schempp, C. Zhang, G. Clemente, “A Coupled RFQ – Drift Tube Combination for FRANZ, LINAC 2008, Victoria, 2008, MOP001, p. 46, (2002); http://www.JACoW.org

[7] V.A. Andreev at al., Injector of High Current Multi-charge Heavy Ion Beam for the TWAC Project, EPAC 2000, THP4B06, http://www.JACoW.org

[8] O.K. Belyaev et al., “IHEP Experience on Creation and Opereation of RFQs”,MOD21, LINAC 2000, Monterey, California, http://www.JACoW.org

[9] P.N. Ostroumov and A.A. Kolomiets, “New Concept for Acceleration of Slow, Low-Charge State Heavy Ion Beams”, Proceedings of the 2001 Particle Accelerator Conference, Chicago, p.4077.