ACCELERATING STRUCTURE WITH COMBINED RADIO-FREQUENCY FOCUSING FOR ACCELERATION OF HEAVY IONS A/q ≤ 20 TO ENERGY 1 MeV/u

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A general arrangement of initial part for multicharged ion linac (MILAC) with two-segment accelerating structure has been developed. The first segment, an interdigital H-type (IH) accelerating structure with radio-frequency quadrupole (RFQ) focusing provides ion acceleration from 6 up to 100 keV/u with high capture efficiency of injected ions. The second segment consisting of IH accelerating structure based on a combination of alternating phase and quadrupole radio-frequency focusing (CRFF) delivers radial-phase stability to ion acceleration from 100 up to 975 keV/u.

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INTRODUCTION

The studies into application of high-energy heavy ion beams to various fields of nuclear physics and energetics, radiating material technology, medicine, applied science are in progress on the Kharkiv linear accelerator of multicharged ions (MILAC) including investigations of fusion and quasi-fission of heavy nuclei, influence of accelerated charged particles on constructional materials, radionuclide production etc. On this basis it is important to conduct investigations into an optimal initial pre-stripping section of MILAC accelerator.

Nowadays, the initial part of MILAC accelerator includes a high-voltage injector with output energy 33 keV/u and a pre-stripping section with grid focusing POS-15 for acceleration of heavy ions with mass-to-charge ratio A/q ≤ 15 up to 0.975 MeV/u. After leaving the POS-15 section, the accelerated ions pass through a thin carbon film increasing their charge (mass-to-charge ratio becomes A/q ≤ 5) and then undergo acceleration up to 8.5 MeV/u in the main section OS-5. The high-voltage injector and the pre-stripping section with grid focusing POS-15 do not allow acceleration of intense, up to 10 mA in a pulse, heavy ion beams in a wide range of masses.

Replacing grid focusing with focusing by an electromagnetic quadrupole lens placed inside a drift tube encounters certain difficulties. It is well known that the electromagnetic lens as an accelerator technological unit is rather complicated in manufacturing and demands a cooling system and an independent power supply. Focusing rigidity of the quadrupole electromagnetic lens is proportional to particle velocity; therefore it is necessary to use strong lenses for heavy ions at low energy. But it is rather difficult to fit such a lens into a small drift tube that corresponds to low relative velocity β. In our case, the ion relative velocity equals $\beta = 0.0007$ at the pre-stripping section POS-15 inlet and the drift tube length of IH accelerating structure operating at 47.2 MHz in which the first quadrupole is to be placed, makes $\beta\lambda/4 = 1.1$ cm. So, such variant is almost impracticable. Besides, there also exist some difficulties in operating the high-voltage injector.

The objective of this paper is to present the initial pre-stripping section of heavy ion linac which is simple in construction design and at the same time allows an acceleration of wide range of ions, a considerable increase in accelerated beam current, and a simplification of accelerator injector system.

1. THE OPTIMUM CHOICE OF ACCELERATING AND FOCUSING CHANNEL OF THE STRUCTURE WITH CRFF

An alternative to a heavy ion linac with external focusing devices is an accelerator in which an accelerating field is used to focus charged particle beams. The high-current linac – proton injector URAL-30 is one of such accelerators [1]. Another similar accelerator for Au^{31+}_{197} acceleration was built in IHEP (Institute of High Energies Physics, Protvino, Russia) and JINR (Joint Institute for Nuclear Researches, Dubna) [2]. A "double gap" concept was implemented for beam acceleration and focusing in the main section of this accelerator [3]. According to the "double gap" concept, to ensure radial and phase beam stability, an additional electrode was introduced into each accelerating gap dividing it into two parts: axisymmetric and quadrupole. Particle acceleration and phasing occurred in the former part while a quadrupole field component was generated due to introduction of additional electrodes "horns" in the latter one. Periodic change in RF quadrupole orientation in the adjacent accelerating periods provided radially stable particle movement.

The usage of such structures allows elimination of complex electromagnetic lenses with independent cooling system and power supply from the accelerator design and simplifies accelerator manufacture and maintenance. The drawback of this method is rather low acceleration rate.

Contrary to the "double gap"-structure, the structure with combined alternating-phase and quadrupole RF focusing (CRFF) includes a combination of "full" axisymmetric accelerating and quadrupole gaps [4]. The usage of such combination provides an increase in acceleration rate and focusing rigidity. Fig. 1 presents the accelerating and focusing section with CRFF consisting of three accelerating gaps and one "doubled" quadrupole section.

The accelerating structure with CRFF as a pre-stripping section of heavy ion linac makes it possible to increase accelerated current and to widen the range of accelerated ions.

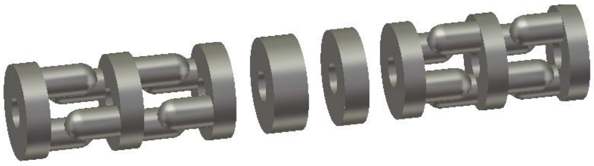

Fig. 1. Fragment of the accelerating and focusing section with CRFF

The pre-stripping section in service today is composed of (1) the high-voltage injector (500 kV), the POS-15 section (1 MeV/u, A/q = 15), and (3) the main section OS-5 (8.5 MeV/u, A/q = 5) as demonstrated on Fig. 2,a.

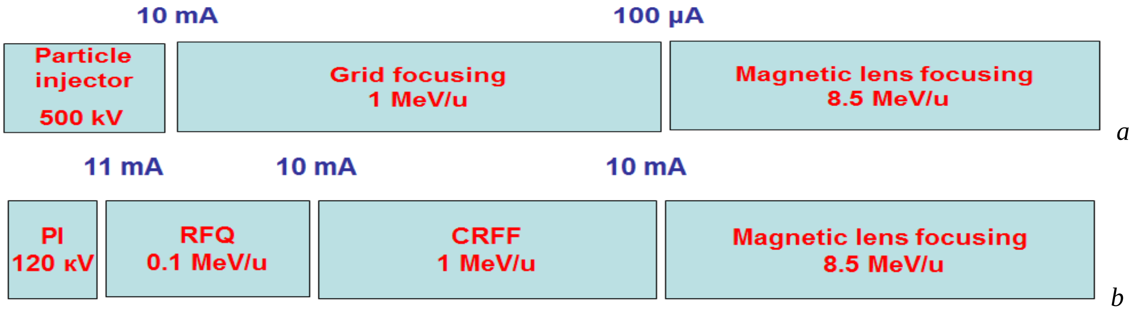

Fig. 2. Schematic representation of linac: a) linear accelerator in service (A/q = 15); b) alternative linac with focusing RF field in pre-stripping section (A/q = 20)

To increase stability of the injecting system we suggest replacing the high-voltage injector with the 120 kV-source. The accelerating part of the pre-stripping section will consist of two segments: the first segment is based on the RFQ structure [5] and the CRFF structure makes the second one (see Fig. 2,b). One of the advantages of the CRFF structure is independence of RF quadrupole focusing from the particle velocity. It makes possible to shorten the RFQ segment length since this segment only forms a bunch and does not accelerate it.

The RFQ electrodes measure ~ 3 m in length, energy ranges 0.006…0.1 MeV/u, beam capture efficiency reaches ≥ 80% under acceleration mode at input current of 10 мА (A/q = 20).

The CRFF segment length, the value of accelerated current and beam emittance vary with the focusing period structure. The following patterns for the focusing period have been considered:

1. The focusing period has 6 axisymmetric accelerating gaps – FOOODDOOOF, where F is an accelerating period with a focusing quadrupole that focuses in transverse direction (say, along X-coordinate), D denotes a defocusing segment, and O represents an axisymmetric accelerating gap.

2. The focusing period includes 8 axisymmetric accelerating gaps – FOOOODDOOOOF.

3. The focusing period with 10 axisymmetric accelerating gaps – FOOOOODDOOOOOF.

4. The mixed focusing period: the pattern is FOOODDOOOF for energy range 0.1…0.4 MeV/u and FOOOOODDOOOOOF for energies 0.4…1.0 MeV/u.

As expected, the first-pattern focusing period provides the maximum value for current under acceleration mode, the minimum increase in beam emittance and the maximum length of the accelerating channel. The CRFF segment measures ~ 8 m in length, energy ranges 0.1…1.0 MeV/u, beam capture efficiency reaches ≥ 98% under acceleration mode at input current of 18 мА (A/q = 20). Fig. 3 depicts the phase portrait, the vertical and horizontal beam profiles at various positions inside the pre-stripping accelerator section.

The patterns #2 and 3 produce the smaller length of the accelerating channel, i.e. 7.2 and 6.0 m correspondingly, but demonstrate lower accelerated current (≤ 8 mA) and higher beam emittance. The pattern #4 consisting of two different periods is a compromise. In this case the CRFF segment length is ~ 7 m and the accelerated current is ≥ 9.8 mA.

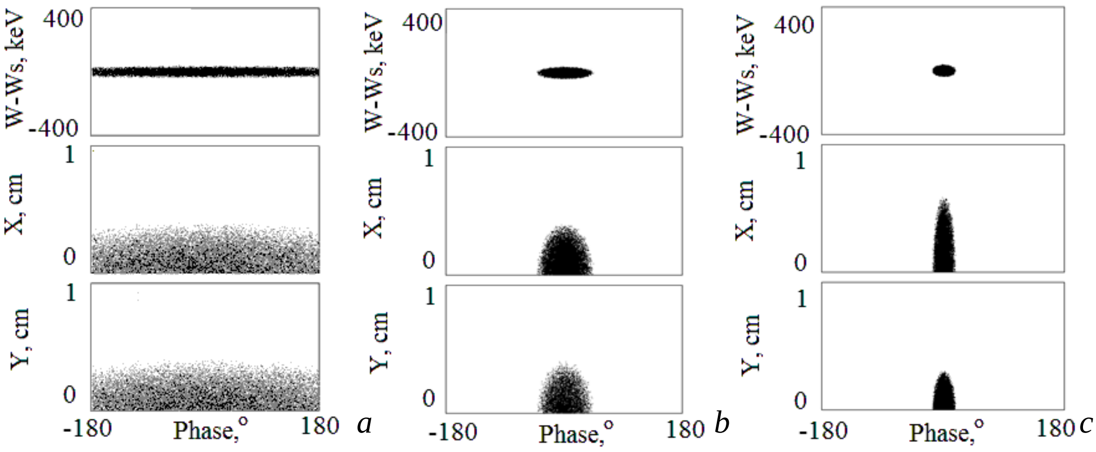

Fig. 3. Phase portrait, vertical and horizontal beam profiles: a) at the entry-point of the RFQ structure; b) at the entrance to the CRFF structure; c) at the output of the CRFF structure

2. REALIZATION OF THE ACCELERATING AND FOCUSING CHANNEL WITH CRFF ON THE BASIS OF INTERDIGITAL STRUCTURE

There are two possibilities to implement the accelerating and focusing structure with CRFF in the pre-stripping section of the heavy ion linac. One way is to insert this structure into one extended resonator; the other way is to use two shorter resonators to simplify RF-field adjustment (Figs. 4 and 5).

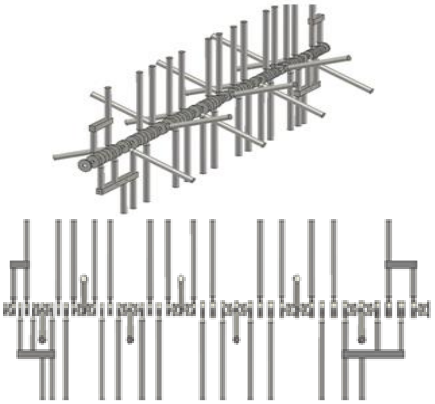

Fig. 4. The schematic view of the accelerating structure with CRFF for energy range 0.1…0.4 MeV/u, the focusing period pattern is FOOODDOOOF

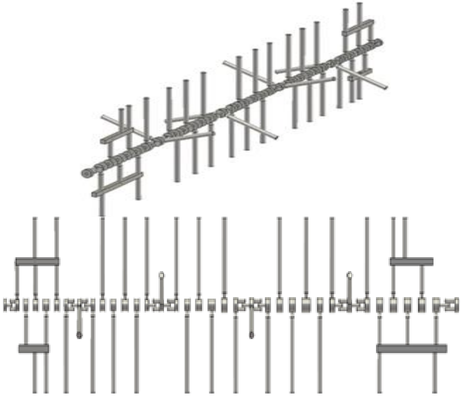

Fig. 5. The schematic view of the accelerating structure with CRFF for energy range 0.4…1 MeV/u, the focusing period pattern is FOOOOODDOOOOOF

Experiments have been carried out on models of the structure with CRFF (1/3). The RF field has been locally tuned by rotation of the shaft holding the central drift tube of the quadrupole segment [6]. It should be noted that in the IH structure it is possible to add an extra shaft symmetrical to the rotated one to enhance the mechanical strength of the whole system (Figs. 6 and 7). Such an addition has almost no effect on electrodynamic characteristics of the structure.

Referring to Fig. 8, the relation between the potential difference in the axisymmetric and quadrupole gaps depends on a tilt angle of the shaft and is local. Global tuning (field flattening in the axisymmetric segments along the whole accelerating structure) has been performed by the usage of end resonant adjusting elements (ERAE).

Fig. 6. The quadrupole segment of the accelerating model structure with CRFF

Fig. 7. General view of the model for accelerating and focusing channel with CRFF with adjusting elements

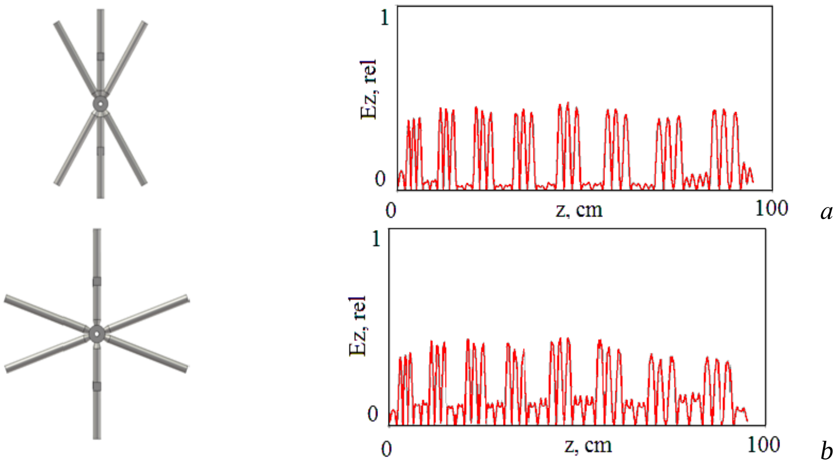

Fig. 8. Example of RF field tuning on the model structure with CRFF for the focusing period FOOODDOOOF: a) the shafts are swung 110° to either side of initial position (left) and corresponding distribution of E_z component of the RF field along the accelerating structure (right); for a corner of bars turn concerning initial position in IH structures on ±110° and distribution E_z component of RF field along accelerating structure; b) the rotation angle is ±160°(left) and corresponding E_z distribution (right)

CONCLUSIONS

Theoretical and experimental studies have shown that the usage of the CRFF accelerating structure allows a considerable simplification in manufacturing and operating of the pre-stripping section of heavy ion linac, a widening the range of accelerated ions (up to $A/q = 20$), and an increase in accelerated current (up to 10 mA). The relatively small length of the CRFF accelerating structure (about 7 m for the focusing period of mixed type) together with the shortened RFQ accelerating section (about 3 m) presents the opportunity to fully exploit available equipment on the limited floor space.

It has also been demonstrated that the usage of adjusting elements designed, developed and put into practice at the NSC KIPT for RF field tuning in the IH structures [7 - 10] makes it possible to obtain necessary for the CRFF structure field distribution along the whole accelerating structure.

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УСКОРЯЮЩАЯ СТРУКТУРА С КОМБИНИРОВАННОЙ ВЫСОКОЧАСТОТНОЙ ФОКУСИРОВКОЙ ДЛЯ УСКОРЕНИЯ ТЯЖЕЛЫХ ИОНОВ С A/q ≤ 20 ДО ЭНЕРГИИ 1 МэВ/нукл.

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Разработана общая схема начальной части линейного ускорителя многозарядных ионов (ЛУМЗИ), ускоряющая структура которой состоит из двух участков. На первом участке ускорения ионов (от 6 до 100 кэВ/нукл.) высокий захват в процесс ускорения инжектированных ионов обеспечит встречно-штыревая (IH) ускоряющая структура с пространственно однородной квадрупольной фокусировкой (ПОКФ), на втором участке (от 100 до 975 кэВ/нукл.) радиально-фазовая устойчивость ионов достигается с помощью IH-ускоряющей структуры на основе комбинации переменно-фазовой и квадрупольной высокочастотной фокусировок (КВЧФ).

ПРИСКОРЮЮЧА СТРУКТУРА З КОМБІНОВАНИМ ВИСОКОЧАСТОТНИМ ФОКУСУВАННЯМ ДЛЯ ПРИСКОРЕННЯ ВАЖКИХ ІОНІВ З A/q ≤ 20 ДО ЕНЕРГІЇ 1 МеВ/нукл.

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Розроблено загальну схему початкової частини лінійного прискорювача багатозарядних іонів (ЛПБЗІ), прискорююча структура якого складається з двох ділянок. На першій ділянці прискорення іонів від (6 до 100 кеВ/нукл.) високе захоплення в процес прискорення інжектованих іонів забезпечить зустрічно-штирьова (IH) прискорююча структура з просторово однорідним квадрупольним фокусуванням (ПОКФ), на другій ділянці (від 100 до 975 кеВ/нукл.) радіально-фазова стійкість іонів досягається за допомогою IH-прискорюючої структури на основі комбінації змінно-фазового та квадрупольного високочастотного фокусувань (КВЧФ).