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NEW CONCEPT OF THE MAIN PART OF MULTICHARGED IONS LINEAR ACCELERATOR ON THE COMBINED RF FOCUSING BASIS

S.S. Tishkin, O.F. Dyachenko
National Science Center "Kharkov Institute of Physics and Technology", Kharkiv, Ukraine
E-mail: tishkin@kipt.kharkov.ua

A new concept of the main part of multicharged ions linear accelerator (MILAC) NSC KIPT on the combined RF focusing (CRFF) basis is proposed. In CRFF acceleration and focusing of the charged particles occurs at the expense of the same accelerating field. Absence of an external focusing field sources a design and operation of the accelerator main part considerably simplifies. The construction principle of accelerating&focusing channels with CRFF is considered. The mathematical modeling findings of a beam dynamics for particles with mass-to-charge ratio of A/q=5 in the energies range of 1…9.2 MeV/u are resulted. Realization of this focusing method on a basis of an interdigital H type accelerating structure is proposed.

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INTRODUCTION

Multicharged ions linear accelerator (MILAC) NSC KIPT [1] has been put into operation more 60 years ago and now it needs in a serious reconstruction.

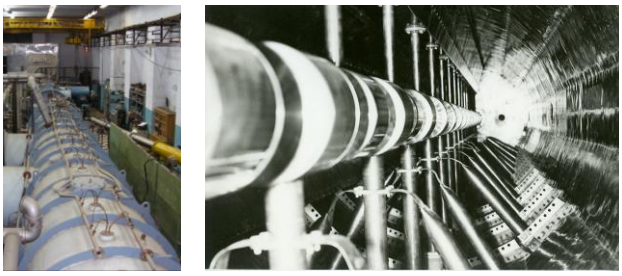
First of all, it concerns of the accelerator initial part. Structurally it consists of a high-voltage injector on 500 kV and prestripper section PSS-15 with grid focusing for acceleration of heavy ions with mass-to-charge ratio of A/q≤15 up to energy of 0.975 MeV/u [2]. Thus use of the such high-voltage injector an accelerator operation seriously complicates, and application of the grid focusing a pulse current of accelerated particles (~10 µA at 10 mA injection current) considerably reduces.

In work [3] for the purpose of work stability increase of an injector system the new high-voltage injector on 120 kV is offered to establish. And instead of the structure with grid focusing for increase of an accelerated particles current and expansion of an accelerated ions range is offered to use section with RFQ focusing (with energies range of 0.006…0.1 MeV/u) and two sections with combined RF focusing (CRFF) (first section with energies range of 0.1…0.4 MeV/u and second section – 0.4…1 MeV/u). Combined RF focusing is realized on the basis of an interdigital H type accelerating structure (IDHAS) [4 - 6] on 47.2 MHz working frequency. Such modernization will allow to expand of accelerated ions kind with A/q≤15 to A/q≤20 and increase of the output pulse current to 10 mA.

After prestripper area the accelerated ions pass through a thin carbon layer where their charge increases to the mass-to-charge ratio A/q≤5 and are accelerated in the main section (MS-5) up to energy of 8.5 MeV/u. For the main section new constructive decisions have been applied and adjusting devices are developed. It has been decided to establish a drift tube of one parity on the general plate bracket (comb) by means of short stems while drift tubes of other parity are fixed on adjusting stems with two additional stems. For increase of IDHAS efficiency it is necessary to reduce capacitor loading of a structure. Application quadrupole focusing imposes certain restrictions on length and diameter of drift tubes. Being guided by positive experience of use biperiodic character of quadrupoles disposition on accelerator UNILAC, the similar constructive decision has been applied. The drift tubes located on a plate bracket, did not contain quadrupole lenses and their diameter increased from the input end of structure to the output end.

Action of adjusting stems was supplemented with other tuning elements (resonant type) which have been developed for the first time and named by end resonant tuning elements (ERTEs). Constructively they represent the quarter wave resonant vibrators formed on the ends of the plate bracket with the help undercuts it from the side of a resonator wall and shorten at the expense of capacity of drift tubes placed on them.

By means of the developed methods combination of adjustment for the first time it was success to generate uniform distribution of an accelerating field in the resonator of the big length for the main section (MS) MILAC. It provided the highest rate of acceleration: almost twice above, than in former section on Alvarets structure. The resonator length from 16.2 to 11.25 m was thus reduced (at the same diameter 1.5 m), A/q from 3.5 to 5 and working wave length in 3 times (6.3 m) were raised. The last has allowed to increase the longitudinal sizes of drift tubes, having reduced their quantity in 2.2 times (from 88 to 40, of them only 20 with quadrupole lenses). The MILAC main section MS-5: general view (a); interiors (b) is presented on Fig. 1 [6, 7]. For the first time on MS model possibility of smooth regulation of ions energy at the expense of creation of various extent field areas is shown [8].



a *b*

Fig. 1. MILAC main section MS-5: general view (a); interiors (b)

For the particles focusing in this section 20 electromagnetic quadrupole lenses are used. Lenses are the difficult technical devices demanding an independent food and cooling. For an operating time these systems have appreciably worn out and demand repair or replacement.

The fundamental solution of this problem is use of the most accelerating field for acceleration and focusing of the charged particles beams. In this work a new concept of the main part of multicharged ions linear accelerator (MILAC) on the combined RF focusing (CRFF) basis is presented.

In this case necessity of use of the electromagnetic lenses established in the drift tubes, and also systems of their food and cooling completely disappears.

NEW CONCEPT OF THE MILAC MAIN PART AND THE SCHEME OF ITS REALIZATION

Generally the problem of an accelerating and focusing path construction of the linear accelerator is three-dimensional and can include all known support ways of the particles radially-phase stability. Now such two methods are mainly used: RF quadrupole focusing [9 - 11] and alternating-phase focusing APF [12 - 15].

Their sharing (combined RF focusing [16 - 19]) is physically consistent and allows to build accelerating and focusing paths of linear accelerators for various of particle kinds and energy ranges.

Advantage of such combined method consists in the following. In APF for creation of the movement stability of charged particles bunch the unique mechanism – axisymmetric RF field is used. Thus to provide the movement radial stability of charged particles bunch probably only at the expense of the longitudinal stability weakening and on the contrary. Such rigid link between stability of the longitudinal and transverse movement strongly complicates working out of the accelerator channel in APF case. It's possible to weaken this link, using structure of an accelerating and focusing period APF with inclusion of the support additional mechanism of the radial stability of charged particles beam movement in the form of RF quadrupole field. In this case it's possible considerably to weaken a stability link of radial and longitudinal movement of the charged particles and that to simplify working out of the accelerator and considerably to increase a value of accelerated particles current.

Structurally accelerating path with CRFF represents a combination of gaps with quadrupole field symmetry between which the certain quantity axisymmetric gaps is located. Quadrupole field component is created by introduction in accelerating gap of additional electrodes which fasten on the drift tube ends (Fig. 2). It's possible to present structure of the accelerating and focusing period in the form of FOOODDOOOF (where F is the accelerating period containing quadrupole area, focusing in one of coordinates direction of the transverse plane, D denotes the defocusing quadrupole area, O represents the axisymmetric accelerating gap). Usually axisymmetric gaps number is 3-5. The more such gaps, the above acceleration rate and less value of the accelerated particles current and on the contrary.

Important problem is possibility of an effective practical realization of the accelerating channel such type in the accelerating structure. In the given energy range it's proposed to use IH structures (IDHAS) with mounting of the drift tubes on the individual stems.

Quadrupole field component it's carried out at the expense of introduction in accelerating gap of an additional electrode that leads to reduction of an electric durability of the quadrupole area. Therefore there is a necessity of decrease in a potential difference on the quadrupole areas relative to the axisymmetric gaps. And with growth of particles speed this difference should increase. It's connected by that for effective acceleration the potential difference on the axisymmetric gaps should increase proportionally ion speeds. In quadrupole gap the potential difference is limited to gaps electric durability and practically remains to a constant along accelerating structure. Therefore there is a necessity of "smooth" increase of a potential difference between quadrupole gap and axisymmetric gap along the accelerating and focusing channel. For IH structure to carry out such adjustment it's possible azimuthal turn of a stem on which the central drift tube of the quadrupole focusing area fastens.

NUMERICAL MODELING OF A BEAM DYNAMICS IN THE MILAC MAIN PART

A beam input parameters which used at the numerical modeling of a beam dynamics are resulted in Table 1. An acceleration rate, a value of the accelerated particles current and a beam emittance growth in the process of acceleration depend on a structure of the focusing period. Two variants of the focusing period: 10-gap and 12-gap accelerating and focusing period with CRFF are presented in Fig. 2. In the first case the focusing period contains 6 axisymmetric gaps with –23° phase of the synchronous particle and 4 gaps with quadrupole symmetry of the transverse field; the synchronous particle phase is 0°. In the second case the focusing period contains 8 axisymmetric gaps with –20° of the synchronous particle and 4 gaps with quadrupole symmetry of the transverse field; the synchronous particle phase is 0°.

Also envelopes and bunch phase extent for each of these two periods, calculated under Trace-3D program are resulted. The program is developed in Los-Alamos national laboratory [20]. It allows to define evolution of a beam envelopes on the focusing period taking into account of space charge forces. It's propose that the accelerator channel consists of the focusing periods coordinated among themselves. Since influence of a beam space charge forces at most in an initial part of the accelerating channel for definition of a beam movement character it's enough to consider the first focusing periods. The particle bunch is represented triaxial ellipsoid, gaps action is considered in approach of a thin lens. Following designations are used: RFQ is the quadrupole area, G is the axisymmetric gap center, a continuous curve denotes the beam envelope in the horizontal direction (red colour), a dotted curve denotes the beam envelope in the vertical direction (dark blue colour), a line in the top half of a drawing (green colour) is the bunch phase extent. A value of a current is 60 mA for 10-gap period and 40 mA for 12-gap period. An average gradient of the transverse RF field in a gap with quadrupole symmetry is 60 kV/cm^2, the maximum intensity of a gap electric field is 100 kV/cm.

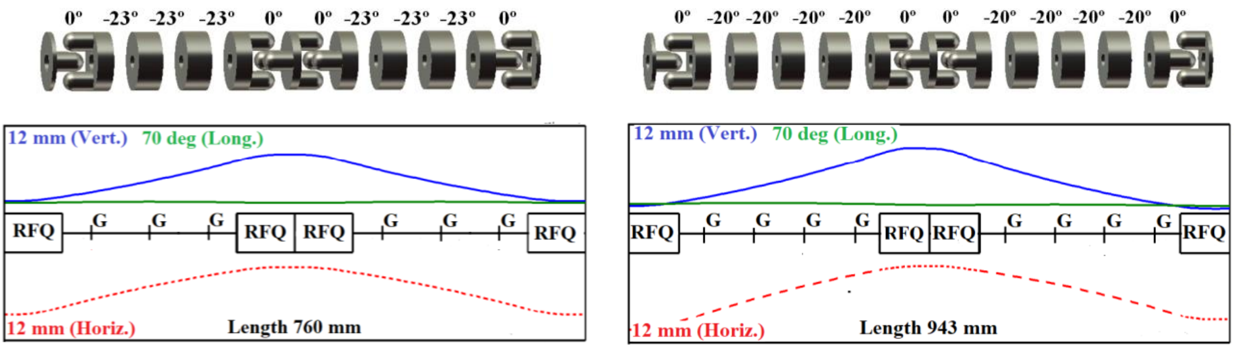
Table 1

Beam input parameters

Parameter	Value
Mass-to-charge ratio (A/q)	5
Operating frequency, MHz	94.4
Transversal emittance, mm·mrad	
$\varepsilon_{n,x}(90\%)$; $\varepsilon_{n,x}(rms)$	0.720; 0.167
$\varepsilon_{n,y}(90\%)$; $\varepsilon_{n,y}(rms)$	0.702; 0.165
Longitudinal emittance, degree keV/u	
$\varepsilon_{z}(90\%)$; $\varepsilon_{z}(rms)$	292.6; 67.8

Final calculation of accelerating and focusing channels taking into account of their real geometry and calculation of a beam dynamics were spent in the development environment of linear accelerators with RF focusing APFRFQ [21]. A value of the field maximum intensity on electrodes surface in a gap with field quadrupole symmetry should be less 2Kp (where Kp is Kilpatrick criterion [22]). For frequency of 94.4 MHz 2Kp value is 222 kV/cm. For the account of a space charge forces, a macroparticles PP (particle – particle) method was used. The number of particles, used at numerical modeling of particles dynamics, was 10000. Dependence of the accelerated particles current on the injection current for channels of the consisting from 10-gap and 12-gap focusing periods is presented in Fig. 3. In the first case the maximum pulse current of the particles, passing accelerating channel lossless, makes 55 mA, the output current at the injection current of 90 makes 81 mA. In the second case their values accordingly is equal 35 and 62 mA. The projections of a phase-space volume of beam to planes *xx'*, *yy'*, *xy*, $\Delta\varphi\Delta W$ (where $\Delta\varphi$, ΔW are phases and energies difference of the particle and synchronous particle) on an input of the MILAC main section which were used for modeling of a beam dynamics with a current of 10 mA are presented in Fig. 4.

The projections of a phase-space volume of beam to output for two variants of the focusing periods are presented in Fig. 5. For simplification of parameters adjustment of an accelerating and focusing canal the MILAC main area is broken into three resonators. Each resonator contains whole number of the focusing periods. The calculated resonator parameters and the beam characteristics on output of the MILAC main area with 10-gap and 12-gap focusing period are resulted in Table 2.



a *b*

Fig. 2. Distribution of the synchronous phases in accelerating gaps, vertical and horizontal beam envelopes, bunch phase length: 10-gap accelerating and focusing period with CRFF (a); 12-gap accelerating and focusing period with CRFF (b)

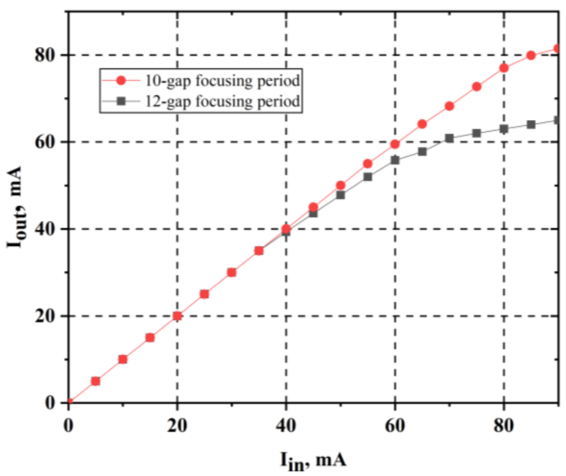


Fig. 3. Dependence of the accelerated particles current on the injection current for 10-gap and 12-gap focusing periods of the MILAC main area

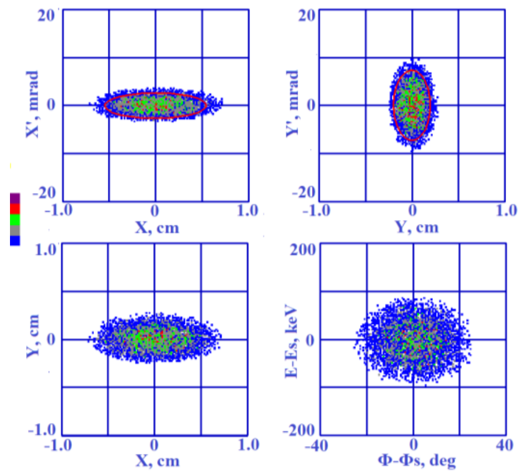


Fig. 4. Calculated projections of a phase-space volume of beam to input of the MILAC main section at a current of 10 mA

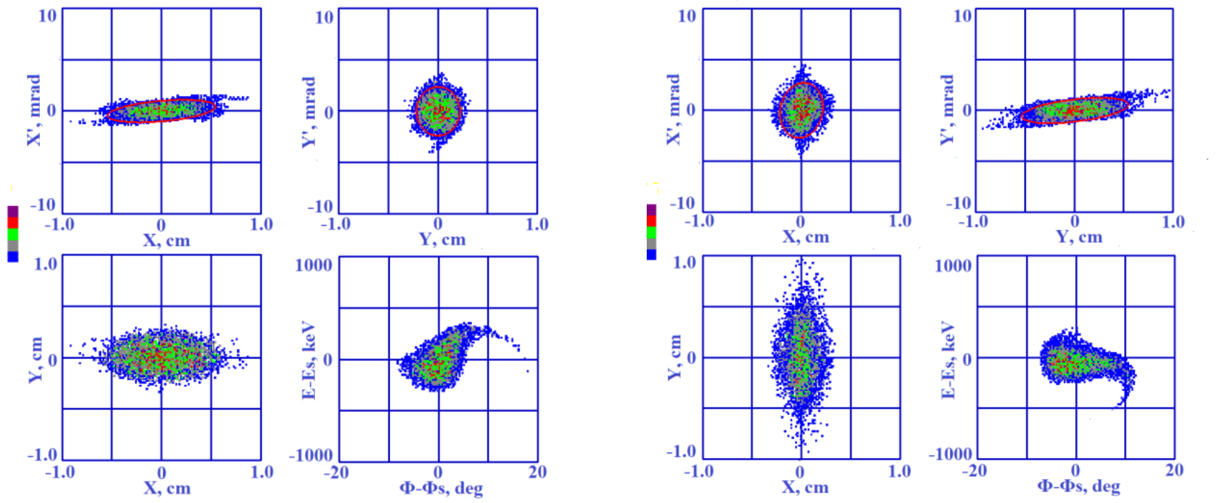


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Fig. 5. Calculated projections of a phase-space volume of beam to output of MILAC main area for the 10-gap (a) and 12-gap (b) variants of the focusing periods (a current of 10 mA)

Table 2

Calculated resonator parameters and beam characteristics of MILAC main area with 10-gap and 12-gap focusing periods

Parameter	10-gap focusing period			12-gap focusing period		
	resonator number			resonator number		
	1	2	3	1	2	3
Output energy, MeV/u	3.08	4.80	8.40	3.11	6.41	9.20
Resonator length, cm	406.0	449.2	572.8	336.7	567.3	490.0
Gaps number	40	30	30	36	36	24
Drift tube aperture radius, cm	1.2	1.2	1.2	1.2	1.2	1.2
Transverse emittance, mm·mrad						
$\varepsilon_{n,x}(90\%)$	0.754	0.780	0.792	0.754	0.825	0.868
$\varepsilon_{n,x}(rms)$	0.176	0.183	0.182	0.186	0.187	0.195
$\varepsilon_{n,y}(90\%)$	0.768	0.772	0.740	0.917	0.853	0.902
$\varepsilon_{n,y}(rms)$	0.177	0.181	0.173	0.206	0.194	0.204
Longitudinal emittance, degree keV/u						
$\varepsilon_z(90\%)$	315.0	317.1	321.2	333.5	331.7	340.1
$\varepsilon_z(rms)$	78.0	75.7	77.8	89.1	81.4	84.7

CONCLUSIONS

A new concept of the MILAC main area on the basis of the CRFF which excludes necessity of use of the electromagnetic lenses, is more reliable and much easier in realization and service. At that such type of focusing does not concede to classical methods which use a principle of the autofocusing and external focusing devices, neither on an acceleration rate nor on a value of the accelerated particles current. We will notice that at a calculated current of 10 mA for particles with A/q=5 the maximum current of accelerated particles passing through accelerating and focusing channel lossless makes 35 mA (output energy of 9.2 MeV/u).

That testify to a considerable “safety factor” on the maximum current of focusing this type. The CRFF feature is necessity of creation in the accelerating and focusing channel of the RF field amplitude of a special form. For practical realization of the similar field configuration it’s offered to use IH structure with fastening of drift tubes on the individual stems. Demanded distribution of the RF field amplitude along accelerating channel is carried out by azimuthal turn of stems on which the central drift tubes of areas with quadrupole field symmetry fasten.

Value of a working frequency in the MILAC main section makes 47.2 MHz. Such value is chosen to provide acceptable length of drift tubes for placing of the magnetic quadrupole lenses. At use CRFF of such necessity is not present. It allows to pass to a multiple working frequency of 94.4 MHz in comparison with prestripper area. Thus increases gaps electric strength and decreases resonator diameter approximately in 2 times.

Absence of the external focusing devices, reliability and simplicity in use allows to draw a conclusion on perceptivity of use of the presented concept by working out of a powerful linear accelerators of heavy ions for carrying out of a nuclear and physical and materials technology researches.

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НОВА КОНЦЕПЦІЯ ОСНОВНОЇ ЧАСТИНИ ЛІНІЙНОГО ПРИСКОРЮВАЧА БАГАТОЗАРЯДНИХ ІОНІВ НА БАЗІ КОМБІНОВАНОГО ВЧ-ФОКУСУВАННЯ

С.С. Тішкін, О.Ф. Дьяченко

Запропоновано нову концепцію основної частини лінійного прискорювача багатозарядних іонів (MILAC) ННЦ ХФТІ на базі комбінованого високочастотного фокусування (КВЧФ). У КВЧФ прискорення й фокусування заряджених частинок відбувається за рахунок самого прискорювального поля. Відсутність джерел зовнішнього фокусувального поля значно спрощує конструкцію та експлуатацію основної частини прискорювача. Розглянуто принцип побудови прискорювально-фокусувальних каналів з КВЧФ. Наведено результати математичного моделювання динаміки пучка для частинок з відношенням масового числа до зарядового A/q=5 у діапазоні енергій 1…9,2 МеВ/нукл. Запропоновано реалізацію цього методу фокусування на основі зустрічноштиревої прискорювальної структури.