INTERDIGITAL STRUCTURES OF HEAVY IONS LINEAR ACCELERATORS: THEIR TUNING, BEAMS FOCUSING AND USE (REVIEW)

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The review interdigital H-accelerating structures (IHAS) of the heavy ions linear accelerators developed in NSC KIPT throughout several tens of years is presented. It is shown that in structures with individual stems all kinds of focusings are applicable: quadrupole, grid, alternating-phase (APF, in various variants), high-frequency (in various variants) and their combinations. Corresponding constructive decisions are developed for accelerating structures of different function. Essentially new approaches for their adjustment for the set distribution of an accelerating field and frequency (by countering corner change) and some new regulating elements are offered: the end resonant elements of adjustment (EREA) and inductance-capacitor elements (contrivances). By results of modelling three real accelerating sections which are created at modernization of the multicharge ions linear accelerator were developed. New variants pre-stripping area of the heavy ions accelerator with the relation of mass number to charge A/q = 20 are offered.

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INTRODUCTION

Studying interdigital H-accelerating structures (IHAS) in NSC KIPT has begun V.A. Bomko almost at once after publications J.P. Blewett [1] and J. Pottier [2] and also proceeded the next years under its direct management [3].

At excitation in the empty cylindrical resonator of type H waves field distribution in which there is no axial component of electric field is established. However there is a possibility to pick up an arrangement of accelerating system elements in the resonator in such a manner that between them the longitudinal component of electric field is formed. For example, if drift tubes to connect serially to the opposite sides of the resonator lateral surface there will be a radical redistribution of fields: electric field will be concentrated in gaps between drift tubes, and magnetic around current elements. Such design using a wave of type H, and has been offered for the first time J.P. Blewett in 1956 (interdigital H structure with drift tubes on individual suspension brackets, Fig. 1). One year later J. Pottier has suggested to use for fastening of drift tubes two plate-combs which are located counter on a lateral surface of the resonator and not reaching its edges (Comb structure, Fig. 2).

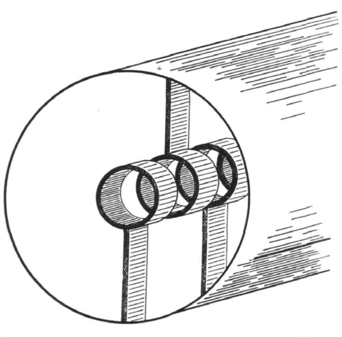


Fig. 1. Accelerating structure, proposed by J.P. Blewett

The work purpose is the review interdigital H-accelerating structures of the heavy ions linear accelerators developed in NSC KIPT. At that possibilities of their adjustment and use in them of all existing kinds of bunches focusing are shown.

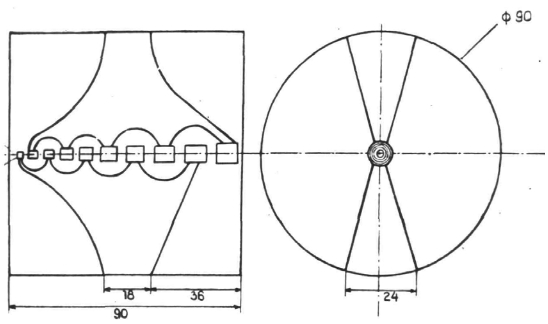


Fig. 2. Comb structure J. Pottier

1. RESEARCH PROBLEM OF THE INTERDIGITAL H-ACCELERATING STRUCTURES

The wave with a longitudinal magnetic field (type H_{111}) form distribution of transversal electric field into rezonator of sinusoidal character. Entering into resonator of counter probes with tubes of drift of one diameter with identical periodicity this dependence do not break. However in the non-uniform structure calculated on acceleration of charged particles, considerable deformation of an accelerating field distribution along structure and frequency change of a wave working length takes place. New methods of adjustment and the effective tuning elements which are not leading to essential deterioration of structure electrodynamic characteristics were necessary for compensation of these changes.

The conducted researches IHAS have been devoted it. Corresponding constructive decisions were developed for heavy ions linear accelerators of different function. At that the basic attention was given to creation of the new sections of the multicharge ions linear accelerator (MILAC).

2. NEW METHODS OF ADJUSTMENT

Great volume of the spent researches on models IHAS has allowed to create the first prototype of this type structure, intended for acceleration of ions with A/q = 7 to energy 1 MeV/u on length of a wave of 6.3 m. This structure has been calculated on sinusoidal distribution of an accelerating field along the resonator. Such distribution was reached by increase of the resonator diameter from 73 cm on the input end to 125 cm on the output end (Fig. 3). The resonator length has made 3.6 m, quantity of drift tubes (identical diameter) 43, grid focusing [4].

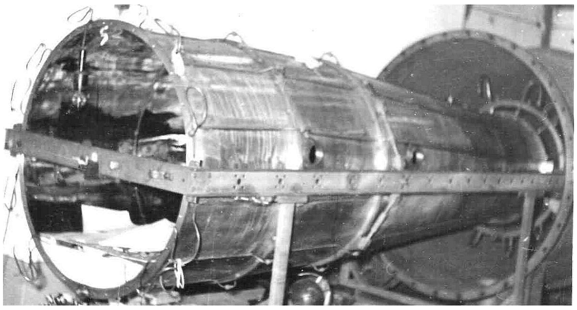


Fig. 3. Conical resonator

Theoretically this method of adjustment has the ideal decision. However the difficult law of diameter change complicates resonator manufacturing techniques. Thus there is no possibility of thin adjustment of cells. The decision of this problem for IHAS with drift tubes on individual stems is found on a way of the refusal of traditional representation about such structure according to which a counter corner, i. e. the corner between two next counter probes, should make 180°. As means of adjustment of non-uniform structure cells possibility of change of this corner from 180° on last, longest cells to sizes of corners on the others which provide the demanded law of a field distribution along structure was used (Fig. 4). It was essentially new approach to adjustment such interdigital H structures [5].

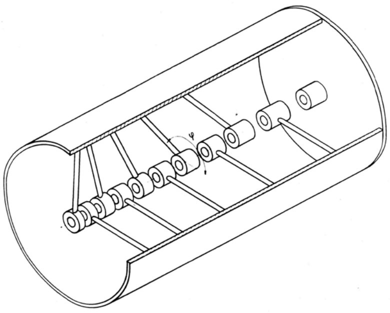


Fig. 4. Accelerating structure with countering corner change φ

The conducted researches have shown that the most effective is the structure with the additional (adjusting, current-carrying) stems symmetrically located concerning positioning stems. The separation of the holders function providing an adjustment of drift tubes and current conductivity, has allowed to reconstruct electric field distributions in more wide range.

The further development of IHAS design for the purpose of MILAC new basic section making was the decision 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 (Fig. 5) [6]. For increase of IHAS efficiency it is necessary to reduce capacitor loading of the structure. Application quadrupole focusing imposes certain restrictions on length and diameter of drift tubes. Being guided by positive experience of use biperiodic character of drift tubes diameters change on accelerator UNILAC [7], 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.

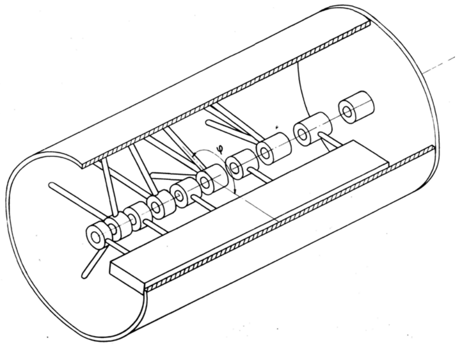


Fig. 5. Accelerating structure with countering corner change and plate bracket

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 elements of adjustment (EREA). 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 (Fig. 6) [8, 9]. If adjustment current-carrying stems was local on each cell separately, but EREA tuning had global character. With their help it was possible to reconstruct (incline) to all distribution of an accelerating field.

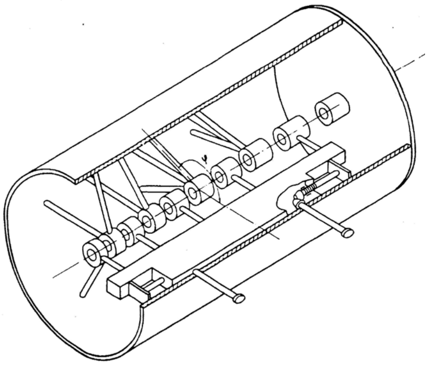


Fig. 6. Accelerating structure with end resonant elements of adjustment

As a result of the spent researches of IHAS tuning on the set (uniform) distribution of electric field and demanded frequency the possibility of these requirements performance by means of the develop adjustment elements is shown: the additional adjusting stems placed on drift tubes of the one row; EREA, and also a choice of the form of a plate bracket and reduction of drift tubes diameters of other row at quadrupole focusing. The data obtained in the process of experimental researches is taken as a principle modernisations MILAC.

3. THE BASIC AND PRESTRIPPER SECTIONS MILAC

The reached successes on development of the IHAS allowed to create, as a matter of fact, the new accelerator. By means of the specified 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 basic section (BS) MILAC. It provided the highest rate of acceleration: almost twice above, than in former section on structure Alvaretsa. The length of the resonator from 16.2 to 11.2 m was thus reduced (at the same diameter 1.5 m), raised A/q from 3.5 to 5 and working length of a wave in 3 times (6.3 m). The last has allowed to increase the longitudinal sizes of the drift tubes, having reduced their quantity in 2.2 times (from 88 to 40, of them only 20 with quadrupole lenses). Interior of the BS MILAC is presented on Fig. 7 [10]. On BS model possibility of smooth regulation of ions energy at the expense of a field areas of various extent creation [11] for the first time is shown.

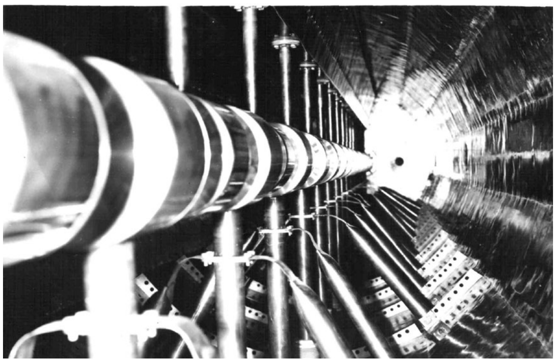
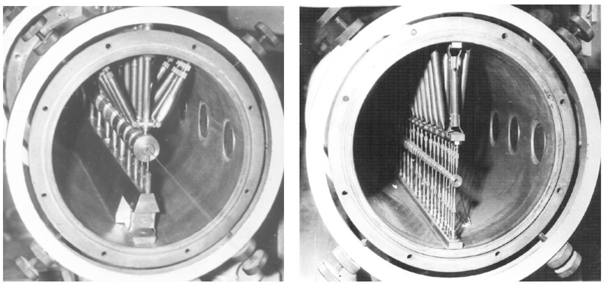


Fig. 7. Interior of the basic section MILAC

At the same time with creation of the BS researches on models prestripper sections (PSS) were conducted. Various variants of focusing were considered: quadrupole and two grid (on different lengths of waves: 12.6 and 6.3 m).

The calculation strong-focusing variant PSS and modelling have shown that at a wave length of 12.6 m the quantity of drift tubes must be 37 (of them 18 with quadrupole lenses) in the resonator length 8,66 m and diameter 1.3 m. Thus in an initial part are used cells with alternating multiplicity of drift. The section is calculated on acceleration of ions with A/q = 22 and is structurally similar BS [12].

The variant with grid focusing reduces the general intensity of an accelerated ions bunch. However high acceleration rate allows to accelerate ions with lower charging (A/q = 30) which intensity above that compensates to some degree losses on grids. Reduction of all drift tubes diameters (unlike quadrupole focusings) which there should be 51 pieces in the resonator length 8.2 m and diameter 1.4 m, raises shunt resistance. New variant of the IHAS [13] in which odd drift tubes are located on longitudinal bearing electrodes, and the adjusting stems established symmetrically and uniformly on length, connect them with a lateral surface of the resonator is developed for this section. For increase in a range of adjustment and from constructive reasons it is offered to shift an axis of structure concerning a resonator axis. The new variant of execution of the EREA in such structure is developed (Fig. 8,a,b) [14]. Use of the described elements of adjustment in variant PSS-30 as have shown researches on model, allow to receive uniform distribution of electric field along structure at wave length 12.6 m.



a *b*

Fig. 8. Models of the quadrupole (a) and grid (b, with the shifted axis of structure) variants of the PSS MILAC

Unfortunately, any of these variants has not been carried out for the various reasons. The prestripper section has been developed on a wave length 6.3 m with grid focusing, with structure in the rectangular resonator (0.90 × 1.16 m) and without shift from its axis. The section in length of 4 m, contains 46 tubes of drift and in it ions with A/q ≤15 are accelerated. Adjustment of section for the set parametres was spent only by change of the drift tubes diameters and three EREA. The mobile lateral wall could be used for frequency change. Accelerating structure of the PSS-15 is shown on Fig. 9 [15].

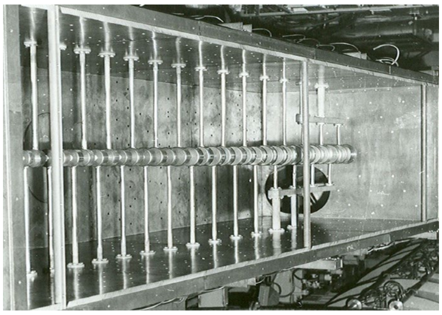


Fig. 9. Accelerating structure of the PSS-15 MILAC

4. DEVELOPMENT OF VARIOUS PROJECTS OF HEAVY IONS LINEAR ACCELERATORS

For reconstruction of the protons linear accelerator of PLAC-9 for the purpose of its transformation into the heavy ions accelerator (A/q = 20) by output energy 1 MeV/u variant of the IHAS with the grid focusing of a bunch calculated on essential increase of a wave length (from 2.1 to 12.6 m) is created. The design of accelerating structure is similar to grid variant of the PSS MILAC, the same resonator length 6 m and diameter 1.5 m (quantity of drift tubes 36) was thus used. As the sizes of the resonator are already set, adjustment for the set frequency was spent, mainly, by means of additional stems [14].

For the first time IHAS with individual stems has been applied with modified alternating-phase focusing (MAFF) a bunch in the basic section intended for acceleration of ions W_{184}^{14+} from energy 419 keV/u to 1.7 MeV/u (the project of an accelerating complex to mass production of track membranes at factory "Tenzor" Dubna, Russia, 1991). The carried out calculation and modelling have shown that at frequency of RF-oscillation 81.4 MHz the quantity of drift tubes should be 58 (length from 1.53 to 19.06 cm) in the length resonator 5.69 m and diameter 0.74 m. Constructively accelerating structure is executed in the form of the IHAS with shifted an axis of a bunch concerning an axis of the resonator and an arrangement of odd drift tubes on longitudinal bearing elements with uniform distribution to them current-carrying adjusting stems. On the input and output ends of accelerating structure are EREA (Fig. 10). For frequency adjustment in small limits in the process of accelerator work, without given distribution of the set accelerating field, it is established on two probes in diameter 2.4 cm (for full-scale structure) on an input and output of resonator symmetrically at an angle 45° to a plane of accelerating structure symmetry. At immersing of all probes on 15.0 cm frequency goes down on 150 kHz.

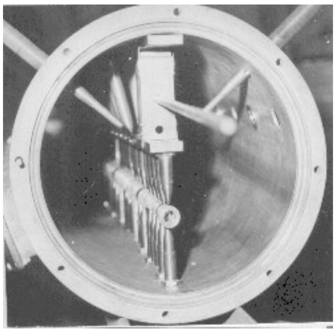
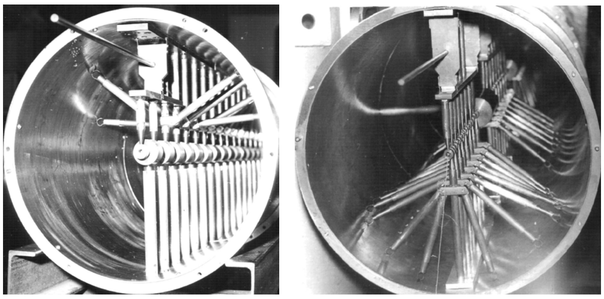


Fig. 10. Model of the basic section with MAFF and lateral probes for frequency adjustment

For Moscow Meson Factory five sections with the IHAS from six under the project of the linear accelerator radioactive nuclides (LARAN), operating in a continuous mode in an energy range from 1 keV/u to 6.5 MeV/u with various types of bunches focusing [16] are investigated. In the first section which accelerates ions from energy 1 to 60 keV/u with A/q = 60 at working frequency 27.12 MHz (develops ITEP) is used RFQ focusing. After acceleration in two sections with magnetic periodic focusing to energy 350 keV/u (at the same frequency and A/q) the bunch of ions is stripped on a firm carbon target. The fourth section is calculated on acceleration with A/q = 7 (as well as the others) to energy 2.786 MeV/u with working frequency 54.24 MHz. Singularity of this and two subsequent sections is realisation of ions acceleration on AFF with a zero synchronous phase [17]. Design feature of 4th and 5th sections is presence in resonators as focusing elements quadrupole triplets between areas of regular accelerating structure (in 4th section – two and 5th – one triplet). Last two sections are excited on frequency of 108.48 MHz. Models of five sections with IHAS (Fig. 11,a,b) which are adjusted on the given field distribution and frequency are created, the transversal geometrical sizes of resonators and all elements are defined, electrodynamic characteristics are measured [18]. Distinctive feature of sections with quadrupole focusing from OS MILAC is that all elements of adjustment both resonant, and not resonant, are located in row of drift tubes without quadrupoles. For the first time in IHAS with individual stems uniform distribution of a field to the areas of structure divided by triplets is received.

Unfortunately, any of these projects has not been realized for the various reasons though workings out are finished to a stage of working drawings.



a *b*

Fig. 11. Models of the second (a) and the fourth (b) sections LARAN

5. THE HELIUM IONS ACCELERATOR

Development and creation of one more prestripper section PSS-4 calculated on acceleration of intensive bunches of easy ions (A/q = 4, the He^+ ions accelerator) from energy 30 keV/u to 1 MeV/u, passed in frameworks of the project of a complex on manufacture radionuclides. In this IHAS for bunch focusing method AFF with step-by-step change of a synchronous phase along the focusing periods is used. For strengthening of efficiency of bunches formation the accelerating field in an initial part of structure increases from a gap to a gap. The octahedral resonator with diameter of the entered circle 1.075 m and length 2.395 m contains 32 drift tubes and is excited on frequency of 47.2 MHz. As a result of the carry out adjusting operations electric field distribution in gaps of accelerating structure close to given is received, but at higher value of resonant frequency (almost on 1 MHz). The problem of resonant frequency change at preservation of demanded distribution of electric field in H-structures always stood sharply enough because coherence of adjustment processes. In this connection new effective inductance-capacitor adjusting devices (contrivances) in the form of the rods located on the side of drift tubes, opposite to their suspension brackets are developed. At a certain design version local fine tuning of cells probably to carry out not only selection of diameter and length contrivances, but also change of a corner of their arrangement concerning an axis of suspension brackets of drift tubes. On Fig. 12 the interior of the PSS-4 (the helium ions accelerator) resonator is presented.

Fig. 12. Accelerating structure of the PSS-4

High efficiency of such inductance-capacitor adjusting system allows to receive demanded electrodynamic characteristics of accelerating structure at identical small diameter of drift tubes that considerably simplifies their design, reduces a radiating background round the accelerator and prevents initiation of the multipacting high-frequency discharge [19, 20].

6. NEW VARIANTS PRESTRIPPER AREA OF THE MILAC

The accelerate and focusing channel high-current of the heavy ions linear accelerator with A/q ≤ 20 on the basis of the IHAS is offered. The channel is calculated on formation and acceleration of a bunch from energy 6 keV/u to 1 MeV/u. Functionally the channel structure includes an area with RFQ focusing (energy from 6 to 100 keV/u) and prestripper section (energy to 1 MeV/u) with combined radio-frequency focusing (CHFF = AFF + RF-quadrupole) [21, 22]. On model possibility of adjustment of structure CHFF on the given distribution of an accelerating field by means of additional stems and EREA (Fig. 13).

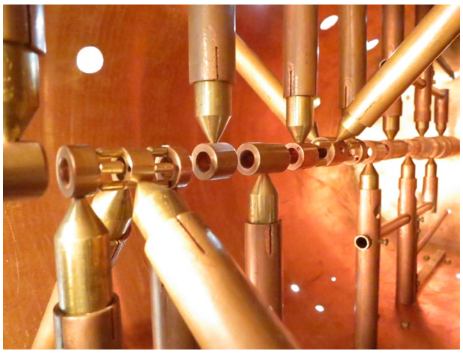


Fig. 13. Model of an accelerating structure with CHFF

The variant of hybrid accelerating structure, in the form of combination of structures with RFQ and grid focusing in one resonator was considered also. For refinement of mathematical modelling results and carrying out of various researches of electrodynamic characteristics of extended hybrid structure scale model is designed [23]. On Fig. 14 the accelerating structure with RFQ is presented.

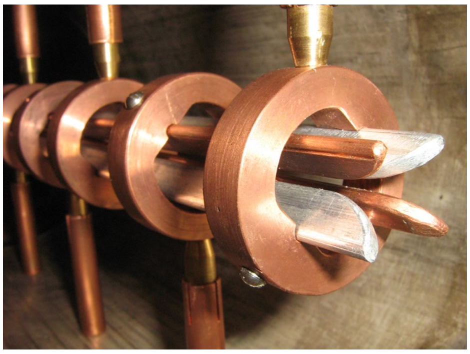


Fig. 14. Model of the RFQ accelerating structure

CONCLUSIONS

The interdigital H accelerating structures of heavy ions linear accelerators were developed in NSC KIPT throughout several tens years. Take into account difficult character of distribution electric and magnetic fields in IHAS, raised on a longitudinal magnetic wave of type H_{111}, new methods of adjustment and formation of uniform distribution of an accelerating field in structure gaps which are based on use of the various inductive, capacitor, resonant adjusting systems are developed and consider in each separate case of feature and appointment of the IHAS. It is shown that in such structures with individual stems all kinds of beams focusings are applicable: quadrupole, net, alternating-phase (AFF, in various variants), high-frequency (in various variants) and their combinations. Three accelerating sections which were created at modernisation MILAC are developed. New variants prestripping area with A/q = 20 are offered.

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ВСТРЕЧНО-ШТЫРЕВЫЕ СТРУКТУРЫ ЛИНЕЙНЫХ УСКОРИТЕЛЕЙ ТЯЖЕЛЫХ ИОНОВ: ИХ НАСТРОЙКА, ФОКУСИРОВКА ПУЧКОВ И ИСПОЛЬЗОВАНИЕ (ОБЗОР)

А.Ф. Дьяченко

Представлен обзор встречно-штыревых ускоряющих структур линейных ускорителей тяжелых ионов, разрабатывавшихся в ННЦ ХФТИ на протяжении нескольких десятков лет. Показано, что в структурах с индивидуальными штангами применимы все виды фокусировок: квадрупольная, сеточная, переменно-фазовая в различных вариантах, высокочастотная в различных вариантах и их комбинации. Для ускоряющих структур различного назначения разработаны соответствующие конструктивные решения. Предложены принципиально новые подходы для их настройки на заданное распределение ускоряющего поля и частоту (путем изменения угла встречности) и несколько новых регулирующих элементов: концевые резонансные элементы настройки и индуктивно-емкостные элементы (контрики). По результатам моделирования разработаны три реальные ускоряющие секции, которые создавались при модернизации линейного ускорителя многозарядных ионов. Предложены новые варианты предобдирочного участка ускорителя тяжелых ионов с отношением массового числа к зарядовому $A/q = 20$.

ЗУСТРІЧНО-ШТИРОВІ СТРУКТУРИ ЛІНІЙНИХ ПРИСКОРЮВАЧІВ ВАЖКИХ ІОНІВ: ЇХ НАСТРОЮВАННЯ, ФОКУСУВАННЯ ПУЧКІВ ТА ВИКОРИСТАННЯ (ОГЛЯД)

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Надано огляд зустрічно-штирових прискорювальних структур лінійних прискорювачів важких іонів, що розроблялися в ННЦ ХФТІ протягом декількох десятків років. Показано, що в структурах з індивідуальними штангами застосовні всі види фокусувань: квадрупольна, сіткова, змінно-фазова у різних варіантах, високочастотна у різних варіантах та їх комбінації. Для прискорювальних структур різного призначення розроблено відповідні конструктивні рішення. Запропоновано принципово нові підходи для їх настроювання на заданий розподіл прискорювального поля й частоту (шляхом зміни кута зустрічності) і декілька нових регулювальних елементів: кінцеві резонансні елементи настроювання та індуктивно-ємнісні елементи (контрики). За результатами моделювання розроблено три реальні прискорювальні секції, які створювалися при модернізації лінійного прискорювача багатозарядних іонів. Запропоновано нові варіанти передобдиркової ділянки прискорювача важких іонів із відношенням масового числа до зарядового $A/q = 20$.