PARTICLE DYNAMIC IN THE ION LINEAR ACCELERATOR BASED ON ALTERNATING PHASE FOCUSING WITH MOVING CENTER OF THE BUNCH

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Abstract

The version of alternating phase focusing in an ion linear accelerator is discussed. It is based on a periodic shift of the bunch from the region of negative phases to that of positive ones and conversely, with a constant excess of the bunch center energy over the synchronous particle energy both in positive and negative phases. The compromise between the inconsistent requirements of radial and phase stability is achieved by selection of phase shift depth, the number of accelerating cells along focusing and bunching regions, and by excess of the bunch center energy over the synchronous particle energy. A high efficiency of the version is demonstrated by the example of calculations of the accelerating structure and beam dynamics of a heavy ion linear accelerator with a high ratio of atomic mass to charge, A/q=32

1 INTRODUCTION

The problem of radial and phase beam stability in accelerating and focusing channel of and linear accelerator for protons and heavy ions has been acute for 50 years in spite the long history of development of such equipment. The method of forming simultaneous radial and phase stability determines the parameters of the accelerating channel as a whole (the angle of capture, rigidity of focusing system, transparency, acceleration rate, accelerated beam current, consumption of HF-power, construction of the accelerating structure etc.).

The idea of alternating phase focusing (APF) was put forward as early as in 50-ties by M.Good [1] and Ya.B. Fainberg [2] independently. It was a new approach to provision of radial and phase stability with focusing by HF-field alone. Further, this method was improved [3,4] and it was proved that acceptable radial and phase stability can be obtained in the case of asymmetric change of the synchronous phase superposed on the bunch center from the region of negative phases (grouping section) to the region of positive phases (radial focusing forces).

The large step forward was the proposition to use the focusing period consisting of several accelerating periods [5]. Nevertheless, the problem of acceleration rate and losses of HF-power remains due the fact that for provision of simultaneous radial and phase stability for this version the synchronous phase was changed to phases which were large in absolute values (-70° and +47°).

There is also an idea of using a structure with zero synchronous phase [6] to achieve radial and phase stability. Under the condition, that the energy of particles exceeds the energy of the synchronous particle, particles from the region of positive phases moved to the region of negative phases. However, in this case only a small part of the bunch is in the region of positive phases and only for a short time. Therefore the imperative condition was using quadrupole triplets which basically provide radial focusing. Using $\varphi_s=0$ results in a small angle of capture that does not exceed 30°. However, the structure with zero synchronous phase was used for heavy ion accelerators [6-8].

In the present work the method of alternating-phase focusing is described that gives a possibility to enlarge essentially radial and phase particle capture to acceleration and to enlarge acceleration rate.

2 THE PRINCIPLE OF APF WITH MOVING BEAM CENTER (MBC)

Version of APF with MBC is based on periodical shift of the bunch from the region of negative phases to the region of positive phases, and conversely, with the constant excess of bunch center energy over the synchronous particle energy both in positive and in negative phases. As a result, at every region of the structure all particles of the bunch move in the direction of the smaller phases in the (ΔW, φ) plane, where ΔW is deviation in the energy of the bunch particles relative to the synchronous particle energy, φ is the phase of the bunch particles. That allows to enhance the focusing and bunching action of the HF-fields. The continuous distortion of the phase portrait of the bunch and shifting of the particles relative to the bunch center is accompanied by the attenuation of the phase oscillations of the particles. The best compromise between the conflicting requirements for the radial and phase stability is achieved by selecting of the depth phase shift, the number of the accelerating cells along focusing and bunching regions, and by the excess of the bunch center energy over synchronous particle energy.

In the accelerating process this moving center glides with reference to the synchronous phase. In all previous versions of APF as well as in accelerating structures with rigid focusing channel and RFQ the bunch center always coincides with the synchronous particle and the energy gain along the accelerating structure was evaluated with the synchronous particle energy. In the version under consideration the concept of “synchronous particle” has no physical meaning as at the moment of passing the center of the gap overall bunch is higher in energy than the conventional particle with which calculation of gap lengths is being carried out. Therefore, we will use the term “calculation particle” instead of “synchronous particle”.

3 STUDY OF BEAM DYNAMICS IN THE LINEAR ACCELERATOR WITH APF AND MBC

Improvement of the APF method with MBC was carried out in the course of calculation of a new prestripping section of the multicharged heavy ion linear accelerator (MILAC) that was designed for ion acceleration with large mass-to-charge ratio (POS-32). This section should replace the existing section designed for A/q=15. That would give a possibility to expand essentially the range of accelerated ion masses.

Optimization of POS-32 characteristics is directed to design an accelerator simple in its construction, cheap, efficient in energy consumption, and with the best beam parameters. The new POS-32 is based on two important innovations: first, a new accelerating structure of the interdigital type is used which is efficient in the three parameters: compactness (large operating wavelength), high rate of acceleration, high shunt impedance [9-11]; second, radial and phase stability is provided with alternating-phase focusing with the moving bunch center [12].

Calculation of accelerating structure and beam dynamics in the course of acceleration was optimized with phase and radial movement and was carried out in one-particle approximation. The fact that we did not take into account repulsing forces of the bunch charge gave a possibility to study in details beam dynamics, the process of bunch forming, and to determine optimum conditions for the largest value of longitudinal and transverse acceptances. As a result of the optimum selection for each of the three degrees of freedom the accelerating structure is obtained, which parameters are listed in the Table I.

Input energy of ions, keV/u	14
Output energy of ions, keV/u	655
Mass-to-charge ratio, A/q	32
Operating frequency, MHz	23,7
Electric field in gaps, MV/m	9,5
Length of accelerating structure, m	6
Number of drift tubes	48
Aperture of drift tubes, mm	16-24
Synchr. phase bunch. regions,deg.	70- 40
Synchr. phase focus. regions,deg.	40-30
Number of bunching regions	6
Number of focusing regions	6
Acceleration rate, MeV/m	3,2
Longitudinal capture, deg.	100
Longitudinal acceptance, keV/u·deg	180
Radial acceptance, mm·mrad	495
Normal. radial accept., π·mm·mrad	0,87
Output energy spread, %	0,93
Output bunch length, deg	20

Beam dynamics calculation is a complicated process of maintenance of the phase-radial stability of bunches during acceleration. In the Fig1.the combined diagram of phase and energy parameters of the particle dynamics along the POS-32 is presented. On the abscissa the sequence numbers of the cells grouped in 12 regions (6 bunching and 6 focusing regions) are given. On the ordinate phase characteristics is at the left, and energy parameters is at the right (total energy of the synchronous particle (W_s) and shift in energy of the bunch center relative to synchronous particle energy (ΔW).

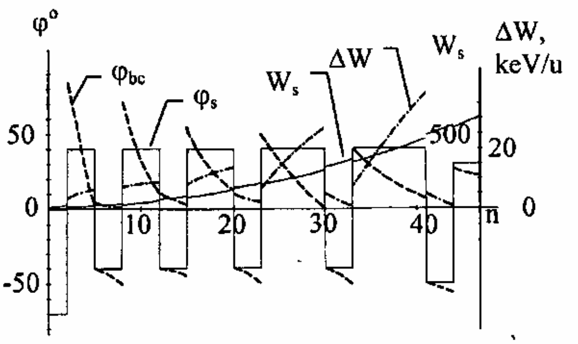

Fig.1. Combined graphic of phase and energy beam characteristics in the process of acceleration for sections of the POS-32 structure

As one can see from the Fig.1, the initial acceleration with bunching take place when the phase is large in modulus (- 70°). In the following bunching regions the phase is equal to - 40°, in the focusing regions it is equal to +40°. The phase of the bunch center (Fig.1, dashed line) in the following bunching regions does not change considerably being, in average, several degrees above the synchronous phase. At the same time the significant shift of the phase of the bunch center occurs during its moving along the focusing regions. At the beginning of every focusing region the center of the bunch enters a center of the accelerating gap at large positive phase that results in significant focusing. Further the center of the beam moves to the smaller phases. Its average value at the focusing regions varies from 44° to 20°. Therefore, in the structure the high acceleration rate is conserved. The excess of the energy of the bunch center over the energy of the synchronous particle W_{bc} - W_c (Fig.1, dashed-dotted line) varies from 2 keV/u at the input of the bunching sections to 1 keV/u at the output. As one can see from the Fig.1 for the focusing regions this value varies in the wider limits.

4 RESULTS OF CALCULATIONS

Radial and phase characteristics of the bunch with passing bunching and focusing regions of the structure are demonstrated in the following schemes. The separatrix that determines the capture of the injected beam to stable acceleration is presented in Fig.2.

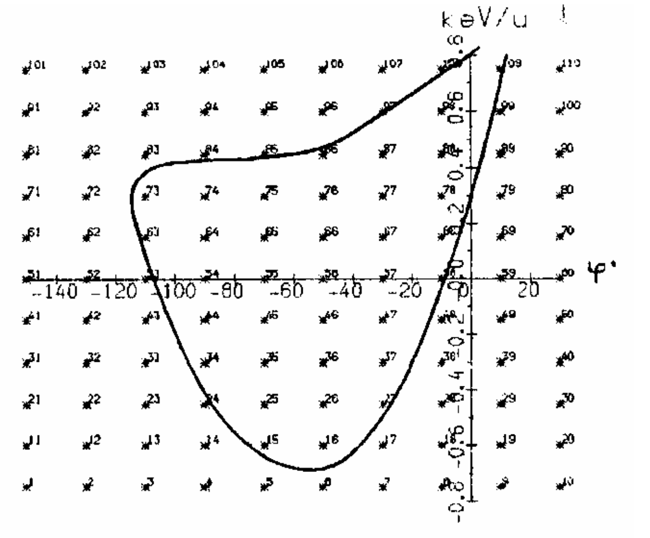

Fig.2. Separatrix determining capture of the injecting beam in the process of stable acceleration.

All particles of the continuous beam being injected in the linear accelerator that have a spread in energy ΔW/W = ±5% and phase extent of 100° are captured in the process of stable radial-phase movement to the designed energy.

The radial trajectory of the particles for input radii of 1, 2, 3, and 4mm with the angular discrepancy of 6, 3, 0, -3, -6 mrad are given in the Fig.3. The trajectories of the stable radial motion correspond approximately to the normalized emittance of the ion beam of 0.2 π·mm·mrad at the input.

Calculation of the radial acceptance of the conditional particle in the center of separatrix was carried out. Its geometrical dimension is 350 mm·mrad, and normalized acceptance is 0.87π·mm·mrad. These values are comparable with those for radial acceptances of RFQ and strong focusing channels. At the same time these results as for radial and phase capture are essentially higher than for structures with the zero synchronous phase [6]. With that we avoided application of complicated systems of quadrupole triplets for additional beam focusing.

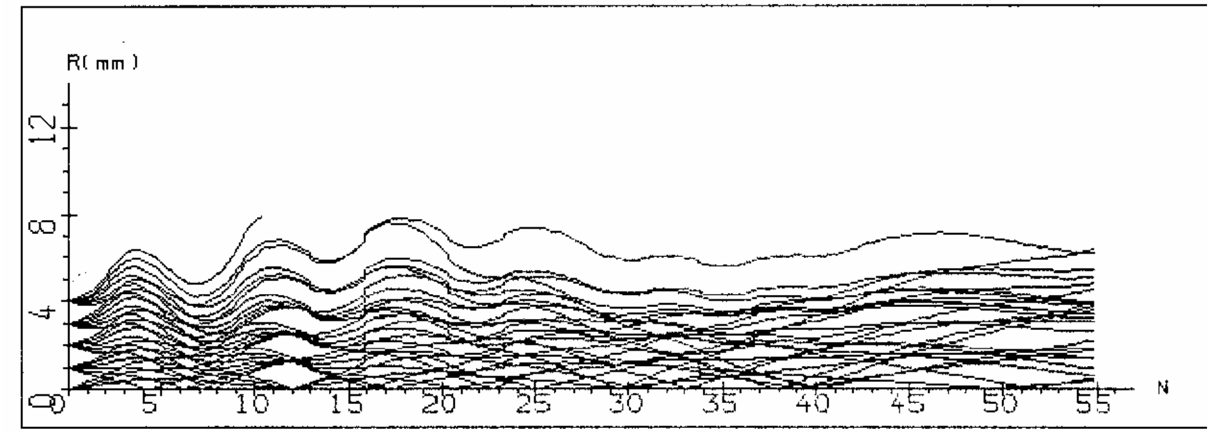

Fig.3. Radial trajectories of particles in POS-32

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