

LINEAR RESONANT ACCELERATORS FOR INDUSTRIAL APPLICATIONS

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INTRODUCTION

Beams of ions with energy up to 10 MeV/A and average current up to 2 mA are required in some cases (deuteron and proton accelerators as neutron sources, high-energy ion implanters, accelerators for charged particle activation analysis) [1,2,3]. Accelerators with alternating-phase focusing (APF) are suitable for these purposes.

These accelerators have been developed and put into operation at MPEI in 1987-1988 (URAGAN-1 [4] and URAGAN-2 [5]). They are designated for research work in material science and ion implantation.

THEORY. CHOICE OF THE ACCELERATOR CHANNEL'S PARAMETERS

The idea of APF was suggested for the first time by Good M.L. and by Fainberg I.B. independently and simultaneously in 1956 [6,7]. However the construction of APF-accelerator became worth-while only after the crucial improvement of this method by Kushin V.V. in 1970 [8]. Further development of Kushin's asymmetric APF has been performed at Kharkov Physics-Technical Institute [9], Moscow Theoretical and Experimental Physics Institute [10], MPEI [4,5,11].

Simultaneous stability of radial and phase motion of particles in an accelerator with alternating-phase focusing is achieved by means of beam interaction with RF-electric field which has synchronous and non-synchronous components. Specific interactions of beam with synchronous and non-synchronous components of RF field is discussed with various approximations in [12-14]. As a result of these investigations a theoretical model was created which is valid for choice of parameters of accelerating channel with alternating-phase focusing. Here we present the basic data of this theory in the simplest variant when RF field in the interaction region may be presented as a superposition of two

synchronous and non-synchronous with beam waves:

$$E_z = E_s I_0(k_s r) \cos(k_s z - \omega_s t + \theta_s) + E_f I_0(k_f r) \cos(k_f z - \omega_f t + \theta_f), \quad (1)$$

$$E_r = E_s I_1(k_s r) \sin(k_s z - \omega_s t + \theta_s) + E_f I_1(k_f r) \sin(k_f z - \omega_f t + \theta_f),$$

where E_z , E_r are longitudinal and transversal components of electric fields; E_s , E_f are amplitudes of synchronous and non-synchronous waves; θ_s , θ_f are phases of harmonics; k_s , k_f are propagation constants of the waves; z , r are longitudinal and transversal coordinates; ω_0 is a cyclic frequency.

If we write the equations of particle motion in the field (1), then transform them into synchronous harmonic-bound coordinate system and apply to them N.N. Bogolubov - Y.A. Mitropolsky's averaging method we will get asymptotic solution of the motion equations, presented in the form of some combination of slow- and fast oscillating motions. The total solutions is used for plotting the beam envelope and for solution of dynamic matching problem for beam and RF accelerating structure. The equations of averaged motion

$$\frac{d^2 \bar{\varphi}}{d\bar{t}^2} = A_s [I_0(\bar{h}) \cos(\bar{\varphi} + \bar{\varphi}_s) - \cos \bar{\varphi}_s], \quad (2.1)$$

$$\frac{d^2 \bar{h}}{d\bar{t}^2} = A_s I_1(\bar{h}) \sin(\bar{\varphi} + \bar{\varphi}_s) - \frac{1}{2} \frac{A_f^2 G}{(1-G)^2} I_1(G \bar{h}) [2I_0(G \bar{h}) - \frac{I_1(G \bar{h})}{G \bar{h}}], \quad (2.2)$$

allow to define the stability conditions of particle dynamics. The above relations use the following symbols: $\varphi = k_s(z - \bar{z}_s)$, $h = k_s r$ - non-dimensional (relative) longitudinal and transversal coordinates; $\bar{\varphi}$, \bar{h} - averaged values of corresponding variables; $A_{sf} = qE_{sf} \lambda / 2\pi W_0 \beta_s$ are relative harmonic amplitudes; q , W_0 are charge and rest energy of particle; β_s is relative velocity of synchronous particle; λ is generator's

field wavelength; $\tau = \omega_0 t$, $\bar{\varphi}_s$ is a synchronous phase mean value; $G = k_f/k_s$, \bar{z}_s is a synchronous particle longitudinal coordinate mean value.

The analysis of Eq.(2.1) shows that the character of longitudinal particle dynamics is defined by synchronous field harmonic exclusively just like in all accelerators with Veksler-McMillan's auto-phasing process. Synchronous harmonic phases defocuses and accelerates beam particles provided synchronous phase is confined within the limits $0 < \bar{\varphi} < \frac{\pi}{2}$.

By the choice of accelerating channel parameters in connection with longitudinal dynamics it is necessary to control the validity of the condition that the region of synchronous motion stability is not overlapped by another regions of stability of the considered system. The quantitative formulation of non-overlapping condition does not present any problems, so we do not give consequent relations.

We conclude this discussion with the note that overlapping effect is dominant in the beginning of the acceleration channel and the extension of the phase stability region limits to reasonable value of the synchronous harmonic's amplitude and reduces the energy increasing rate.

As may be shown from Eq.(2) the nonsynchronous harmonic of RF field only focuses particles. Changing the wave's velocity ratio G and the amplitude of the nonsynchronous harmonic the particle focusing can be controlled.

From Eq.(2.2) one can obtain the frequency of small transverse oscillations:

$$\frac{\Omega(\bar{\varphi})}{\omega_0} = \left[\frac{3}{8} \left(\frac{A_f G}{1-G} \right)^2 - \frac{1}{2} A_s \sin(\bar{\varphi} + \bar{\varphi}_s) \right]^{1/2}, \quad (3)$$

and the phase shift of the radial oscillations per one period of focusing.

$$\mathcal{M}(\bar{\varphi}) = 2\pi \frac{\Omega(\bar{\varphi})}{\omega_0} \cdot \frac{1}{|1-G|}. \quad (4)$$

The transverse motion stability criterium $0 < \mathcal{M}(\bar{\varphi}) < \pi$ should be valid for all inside separatrix. In some cases the maximum value of frequency obtained from (3) is not exact enough. The better result can be got from calculation of the characteristic number of Mathien equation.

The Mathien equation's canonical form

is expressed in terms of the coefficients:

$$Q_r = - \frac{2A_s \sin(\bar{\varphi} + \bar{\varphi}_s)}{(1-G)^2} + \left[\frac{A_f G}{(1-G)^2} \right]^2, \quad Q_r = \frac{A_f G}{(1-G)^2}; \quad (5)$$

$$Q_\varphi = \frac{4A_s \sin \bar{\varphi}_s}{(1-G)^2} - 2 \left[\frac{A_f G}{(1-G)^2} \right]^2, \quad Q_\varphi = 2 \frac{A_f G}{(1-G)^2};$$

The second term in Q_r is due to the periodical changing of the longitudinal motion of the particle and causes the static focusing of the particle.

It follows from (5) that static focusing leads to the phase instability of the particle (second term in Q_φ) which however is compensated by alternating-sign phasing^q i.e. by the phase stability in RF field under given motion of the particle.

Using equations given above the acceleration channel design technique for alternating phase focusing method was developed. After finding the RF field spectrum the drift tubes and acceleration gaps sizes are determined. The multi particles simulation is used to check the results of the accelerator channel design. Every step is supported by the software developed to provide accurate calculations.

LINEAR PROTON ACCELERATORS URAGAN-1 AND URAGAN-2

The constructions of the linear proton accelerators Uragan-1 and Uragan-2 were finished in 1987 and 1988, respectively. The URAGAN-1 linac was developed for the material problems investigation. The URAGAN-2 linac is aimed to be used in high energy ion implantation. The accelerators' parameters are given in Table 1.

Table 1. Parameters of the linear proton accelerators URAGAN-1 and URAGAN-2.

Parameter	URAGAN-1	URAGAN-2
Input energy, keV	60	30
Output energy, MeV	1.1	0.5
Beam current, mA	6	4
RF power, kW	85	25
Frequency, MHz	150	150
Input emittance, cm mrad	0.04	0.05
Particles capture	0.45	0.4
Ion source	duoplasmstron	

In URAGAN-1 linac the spiral loaded cavity is used as an acceleration structure.

In URAGAN-2 linac the interdigital H-(IH)resonator is used as an accelerator system. Using the moving frame with the drift tubes makes the technology process easy and provides the quick changing of the acceleration channel to obtain different output beam energy.

The main parameters of both linacs RF systems are given in Table 2.

Table 2. RF Structures parameters.

parameter	URAGAN-1	URAGAN-2
Resonant frequency, MHz	150	150
Length, mm	480	540
Diameter, mm	284	366
Number of drift tubes	12	22
Outer diameter of drift tubes, mm	24	25
Inner diameter of drift tubes, mm	14	18
Intrinsic (zero load) Q-factor	2800	7500
Shunt impedance, MΩ/m	60	160

Shunt impedance of accelerating structures is defined as $Z = \frac{V^2}{2Pl}$ where $V = \int |E_z| dz$, E_z electrical field strength at the cavity axis, l - cavity length, P - RF power.

CONCLUSION

The job carried out shows that at pulse currents of accelerated beam up to 10 mA in low duty factor mode of operation resonant linacs with alternating-phase focusing are quite competitive with RFQ ones while surpassing the latter in mass-size features.

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