SPATIALLY PERIODIC RF QUADRUPOLE LINAC

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Abstract

Spatially-periodic RF quadrupole structure is proposed as second section of front end of ion linac. It consists of conventional drift tubes and RF quadrupoles. Quadrupoles are 4-vane segments with nonzero electric potential on the longitudinal axis. Thus the accelerating electric field is formed between drift tubes and RF quadrupoles. Moreover accelerating field can be provided even inside the RF quadrupoles. It allows building structures with different focusing lattices and provides high energy gain.

INTRODUCTION

Modern ion linacs have Radio Frequency Quadrupole structures (RFQ) for initial beam formation and acceleration to energy of several MeV. Drift Tube Linac (DTL) with magnetic quadrupole focusing is the most common solution for following acceleration. This scheme allows us to design effective front ends for high energy linacs and linacs with of several MeV for medical or industrial applications as well.

Several accelerating structures with drift tubes and RF focusing have been proposed to build compact, efficient and inexpensive ion linacs in this energy range. They are well known as spatially periodic structures with RF quadrupoles [1, 2]. In spite of inherent merits of these structures and their successful operation over the years, they are not widespread. This can be explained by complexity of their mechanical design, complicated RF design and tuning, more complicated beam dynamics design due to stronger coupling of transversal beam motion with longitudinal one comparing with conventional DTL structures.

This paper presents simple and flexible realization of spatially periodic RF quadrupole focusing structure with considerably reduced disadvantages mentioned above.

FOCUSING LATTICE

Energy gain of a conventional RFQ is limited by transverse motion of particles defined by vane geometry and inter-vane voltage due to limited maximum field at vane surface. Voltage increase leads to reducing of focusing strength and vice verse. Spatial period of focusing structure have to be enlarged to provide both good focusing strength and high energy gain of linac with RF quadrupole focusing [3]. One more realization of spatially periodic RF quadrupole structure proposed in the paper is shown in Figure1.

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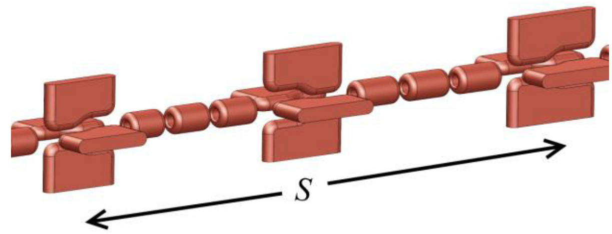

Figure 1: Spatially periodic RF quadrupole lattice.

The structure consists of 4-vane segments separated with a number of conventional drift tubes. The main difference of the structure from well known ones is different transversal displacements of vertical and horizontal vanes of RF quadrupole. It means that there is nonzero electric potential on the quadrupole axis that forms accelerating gap between quadrupole and drift tubes.

Unlike known spatially periodic structures with quadrupoles integrated into the accelerating period the proposed structure provides more freedom of choice for quadrupole length. In case when quadrupole is longer than accelerating period it is possible to form accelerating gap inside RF quadrupole varying displacements of vanes along the quadrupole as it is shown in Fig.1.

If all vertical quadrupole electrodes have the same potential sign the alternating focusing can be provided for focusing period length $S = N\beta_z\lambda$, $N = 1, 3, 5, \ldots$, $\beta_z = v_z/c$ – normalized velocity of ion beam, λ – wavelength of RF field. Case $N = 1$ and RF quadrupole length $L = \beta_z\lambda/2$ corresponds to spatially homogeneous RFQ. Other cases present variations of spatially periodic focusing structures. General properties of these structures are considered in smooth approximation in this paper.

Smooth Approximation

Phase advance μ of particle transverse motion per focusing period of a structure with RF focusing depends on phase of RF field φ when particle is in the center of quadrupole, i.e. $\mu = \mu(\varphi)$. Table 1 shows some possible focusing lattices without taking RF defocusing effect into account. The relation $\mu(\varphi)$ can be approximated as:

$$\mu = \mu_0 + \Delta\mu\cos 2\varphi, \quad (1)$$

here μ_0 and $\Delta\mu$ are mean and spreading values of phase advance μ during RF period (see Fig.2). Analysis of transverse motion using smooth approximation has shown that:

- Focusing gradient G decreases with N for a given value of transverse phase advance or μ_0 increases with N for a given gradient G,

- $|\Delta\mu|$ increases with N for given L and G,
- there are quadrupole lengths L, that correspond to $\Delta\mu = 0$. For $N = 1$, $L = \beta_z\lambda/2$, for $N = 3$, $L = 0.72\beta_z\lambda$, for $N = 5$, $L = 0.8\beta_z\lambda$, etc.,
- $\Delta\mu$ can be positive or negative.

Figure 1 illustrates periodic lattice with $N = 5$, $L \approx 0.8\beta_z\lambda$.

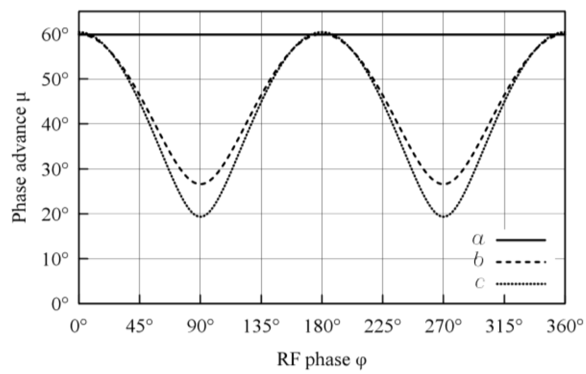

Figure 2: Phase advance in RF quadrupole lattices (parameters are shown in Table 1).

Table 1: Lattice parameters

Parameter	Value				
Curve in Figure 2	*a*	*a*	*a*	*b*	*c*
Focusing period length $S/\beta_z\lambda$	1	3	5	3	5
Quadrupole length $L/\beta_z\lambda$	0.5	0.72	0.8	0.5	0.5
Focusing gradient G/G_{RFQ}	100%	55%	46%	51%	39%
Mean value of phase advance μ_0	60°	60°	60°	44°	40°
Spread of phase advance $\Delta\mu$	0°	0°	0°	16°	20°

RF defocusing effects on transverse motion can be considered by tune shift of phase advance according to:

$$\mu_f^2 = \mu^2 + 2\gamma_0 \sin\varphi_a, \quad (2)$$

$$\gamma_0 = N^2 \frac{\pi ZeUT}{2W_s}, \quad (3)$$

$$\Delta W = eUT\cos\varphi_a, \quad (4)$$

here $\mu = \mu(\varphi)$ - phase advance corresponds to formula (1), γ0 - RF defocusing parameter, φa – phase of RF field in the center of accelerating gap, Z – charge number of a particle, e - proton charge, U – voltage between accelerating electrodes, T – accelerating efficiency, Ws – kinetic energy of a particle, ΔW - energy gain of a particle in one accelerating gap. Thus RF defocusing is an extra reason for spread of overall transverse phase advance μ_f. This is a significant limitation for linacs with long focusing period and high energy gain rate. To attenuate this effect length of focusing period S should be shorter, beam energy W_s and accelerating phase φ_a as high as possible. Adequate choice of quadrupole length L and phase in the center of quadrupole φ can slightly compensate this effect too.

Transverse acceptance of a structure decreases with N, but it can be partly compensated by larger aperture of RF quadrupoles. Figure 3 shows normalized acceptance of spatially periodic RF quadrupole structures depending on quadrupole length L for $N = 1, 3, 5$ and $T = 0$. Acceptance of a structure is so called "dynamical", i.e. Twiss parameters α and β depend of time. It should be considered for beam matching.

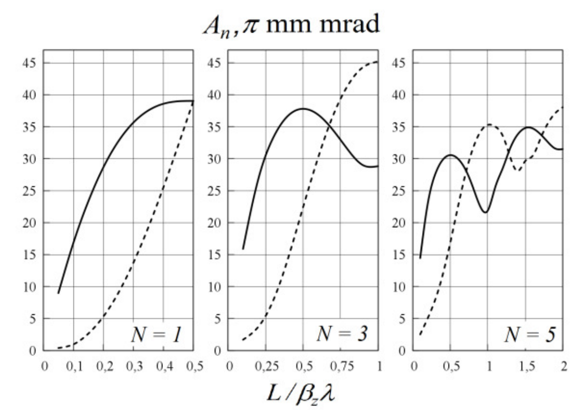

Figure 3: Normalized acceptance of spatially periodic RF quadrupole structures (solid – φ = 0°, dash - φ = 90°).

SIMULATION

Beam dynamics simulation has been carried out to study the focusing properties of proposed structure with 3D field using simulation code TRANSIT. The results of simulation in spatially periodic RF quadrupole focusing structure with focusing period length $S = 5\beta_z\lambda$ and quadrupole length $L \approx 0.8\beta_z\lambda$ are given below. Design of drift tubes and quadrupoles provides almost equal surface electric field. Accelerating electric field along the structure is presented in Figure 4. Modulated quadrupole electrodes provides 73% voltage on longitudinal axis inside quadrupole and 86% voltage on longitudinal axis in gaps between quadrupoles and drift tubes. Energy gain rate 2.5 MeV/m has been achieved. Main beam parameters obtained from computer simulation are presented in Table 2. Transverse envelopes of ion beam are presented in Figure 5. Figure 6 shows transmission characteristic of the linac.

The proposed structure can be based on conventional 4-vane cavity resonator as it shown in Figure 7. Due to the fact that stems join opposite vanes there aren't dipole

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modes near the operating one. Parameters of the linac are shown in Table 3

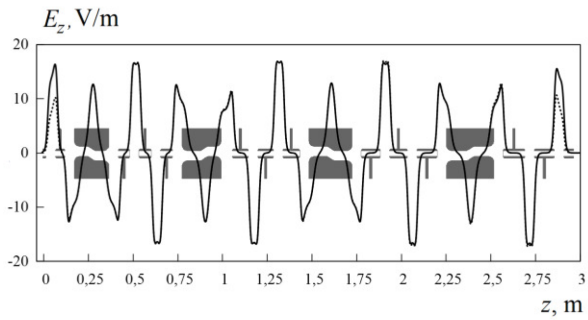

Figure 4: Accelerating electric field along the structure.

Table 2: Beam parameters

Parameter	Input	Output
Charge to mass ratio *Z/A*	1/3	
Beam velocity β_z	0.058	0.093
Beam energy W_s	4.7 MeV	12.17 MeV
Beam current *I*	30 mA	
Transverse normalized RMS emittance ε_n (X/Y)	0.25 / 0.26 π mm mrad	0.31 / 0.32 π mm mrad
Phase length of the bunch Δφ	40°	32°
Energy spread Δ*W*	200 keV	340 keV
Transmission *K*	100 %	

Table 3: Linac parameters

Parameter	Value
Resonator diameter D_R	1050 mm
Resonator length L_R	2960 mm
Voltage *U*	475 kV
Operating frequency *f*	81.36 MHz
Quality factor *Q*	23700
RF power dissipation P_{RF}	490 kW
Normalized RF power P_N	166 kW/m

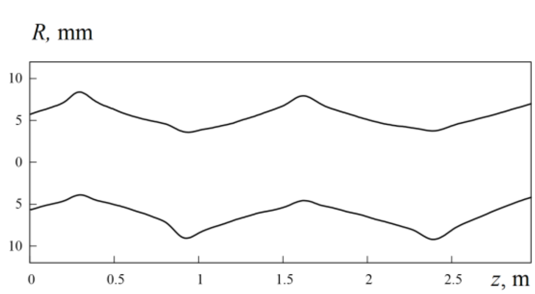

Figure 5: Transverse envelopes of ion beam.

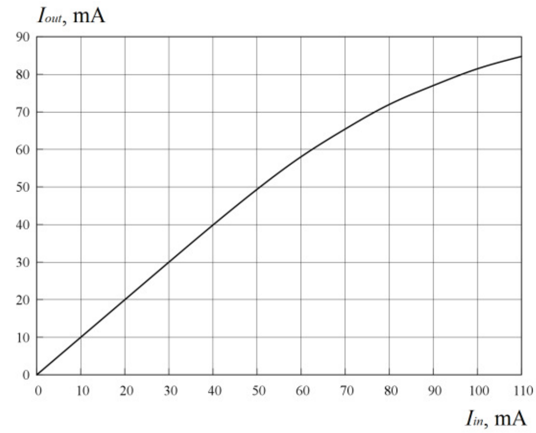

Figure 6: Transmission characteristic of the linac.

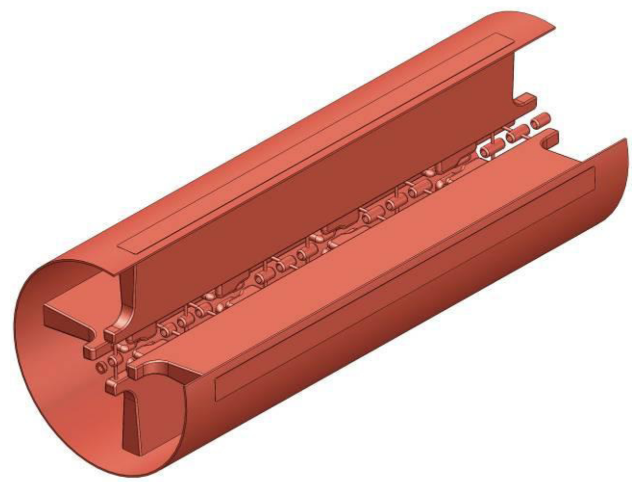

Figure 7: Spatially periodic RF quadrupole linac based on 4-vane cavity resonator.

CONCLUSION

The spatially periodic RF quadrupole focusing structure is presented in the paper. It can provide efficient focusing and acceleration of ion beams within wide range of mass and beam currents.

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