RFQ FOCUSING IN LINACS

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Abstract

RFQ focusing is expedient to use not only for the Initial Part of an Accelerator but for the Main Part of an Accelerator as well. The structures with RFQ focusing are sufficiently small and they are cheaper than the well known DTL (Alvarez) structures with the magnetic quadrupole focusing. Here we present some considerations that let one choose the parameters of the linac with RFQ focusing. These considerations are based on the experience of designing and exploiting such accelerators.

Introduction

Now the Initial Part of an Accelerator (IPA) is based on using the ideas of the adiabatical capturing and the radio frequency Spacial Homogeneous Quadrupole Focusing. The similar linacs, named RFQ, are sufficiently wide spread as the injectors and as independent facilities for industry and scientific investigations. The RFQ focusing in the linacs with $\beta > 0.1$ have not been used anywhere except IHEP. Our 30-MeV proton accelerator with RFQ focusing (URAL-30) has been operating well for more than ten years already.

Initial part of accelerator

A transversal motion of particles, which is characterized by the phase shift of oscillations μ, the minimal ν_{min} and maximal ν_{max} frequency, practically depends on one parameter only, $\tilde{\mu}$. This parameter is proportional to the gradient of the radio-frequency quadrupole component of the field G and quadratically to the wave length. The parameters μ, ν_{min}, ν_{max} depend weakly on the defocusing by the accelerating field component as, to avoid the resonance of the transversal and longitudinal oscillations, the phase shift of the small longitudinal oscillations must be limited:

$$q = 0.7\Omega T < 0.5\tilde{\mu} < 0.5$$

The average beam envelope radius, which determines a coulomb scattering of particles, must be less than the aperture radius ($< 0.8R_a$). The nearest distance from the axis to the electrode tip has the minimal R_{min} and maximal $R_{max} = mR_{min}$ value. The aperture radius is less or equal to R_{min} ($R_a \leq R_{min}$). The multiplier m is the electrode modulation coefficient. The maximal distance R_{max} is limited by maximal acceptable field

$$E_{max} \geq 1.5R_{max}G$$

The field is chosen according to the Kilpatric's criterion and with considerations of the experimental results. The maximal field proportional to the square root of the frequency is given in Fig.1 by two curves:

$$E_{max}(MV/m) = (1.6 \div 1.9)\sqrt{f(MHz)}$$

The field values for the known RFQ's are pointed there by the dots.

The beam current of the RFQ is limited by the transversal coulomb repulsion of iones (Fig.2). For optimal focusing parameters the current is defined by the product of the injection energy and velocity of iones:

$$I \leq 0.2 \cdot 10^{-3} W_0 \beta_0$$

The current is proportional to $\left(\frac{R}{\lambda}\right)^2$. The aperture radius is determined by the equality $R_a = (0.23 \ldots 0.34)\beta_0\lambda$. The dependence of R_a on $\beta\lambda$ is given in Fig.3. The dots point to the value that different RFQ's have.

The electrodes for the RFQ foqusing

The electrodes for the RFQ focusing must satisfy several requirements:

– to provide the necessary gradient of the quadrupole field component;

– to provide the linearity of the field ($E_x \approx Gx$; $Ey \approx -Gy$) within the apperture ($r \leq R_a$);

– to provide the required accelerating rate, i.e. θU;

– the field on the electrode surface must be less than admissible field E_{max};

– the electrodes are to have the capacity load for the resonator as small as possible.

The electrode cross section at the entrance of the RFQ is desirable to be hyperbolic. In this case the tip radii of the electode are equal to their distance from the axis. But in practice the pure hyperbolic approximation is not used.

This shape of the electrodes gives the high surface field and big capacity. Instead of the hiperbolic electrodes the 4-Vane or 4-Rode electrodes are used.

To provide the highest rate of the acceleration one must have the drift tubes on the axes. To minimize the capacity of the electrodes and the field on the tips of the 4-Rode quadrupole we had suggested the 2-gaps electrodes (Fig.4) and the H-resonator for the Main part of the Accelerator (MPA).

In the MPA the bunch of particles is already well formed and its range is within $\pm\varphi_c$. Such bunch is focused by the spatial periodic radio-frequency quadrupole field. The bunch passes the electrical center of the axial symmetric part of the field at the phase $\omega t = -\varphi_c$, and it passes the electrical center of the quadrupole part of the field at the phase near to zero.

In the accelerator URAL-30 the voltages on both gaps are equal. This is explained with the easiness in arranging the intermediate electrode. With the aim to conserve the acceleration rate the gap voltage with the axial symmetrical field U_a must increase proportionally to the iones velocity but the voltage at the gap with the quadrupole field U_q must be constant. The distribution of the gap voltage U_a and U_q is inversely proportional to their capacities C_a and C_q:

$$U = U_a\left(1 + \frac{U_q}{U_a}\right); \qquad \frac{U_q}{U_a} = \frac{C_a}{C_q} < 1$$

The load of the resonator by the electrodes capacity is determined by the series connection of the capacities.

The resonator for the RFQ focusing

For the IPA (for the RFQ's) many types of resonators are proposed. Four chamber (or for vane) resonator has the minimal radio-frequency power losses in the walls (Fig.5). In our facilities we use a 4-chamber resonator with different cells or 2H-resonator (Fig.6).

In the MPA of URAL-30 the H-resonator is used (Fig.7). Higher shunt impedance has a "double chamber" resonator (or 2C-resonator). The power losses per unit in it (Fig.8) are proportional to

$$P/L \approx 10^{-4}(\omega C)^{3/2}U^2$$

Namely, the 2C-resonator will be used in our new proton accelerator with RFQ focusing up to 60MeV (URAL-60). The accelerating rate can reach 2 and more MeV/m. Higher shunt impedance is achieved due to a small capacity load (about $15 \div 20\ pF/m$).

The Table 1 presents some parameters of the Russian linacs with the RFQ Focusing. The linac PL-1 is our first step of the linac designing for the medicine or industry applications.

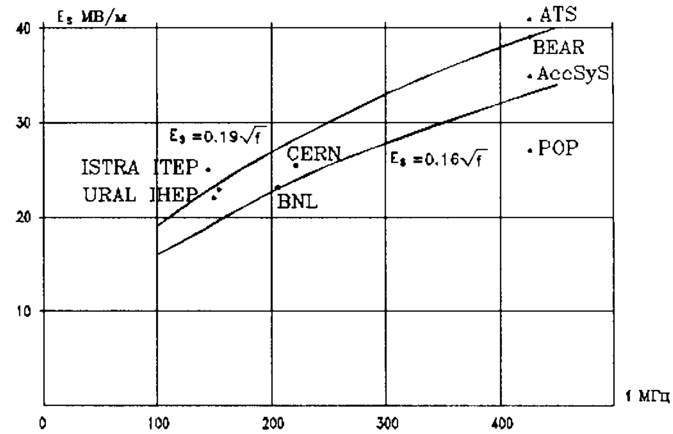


Fig.1

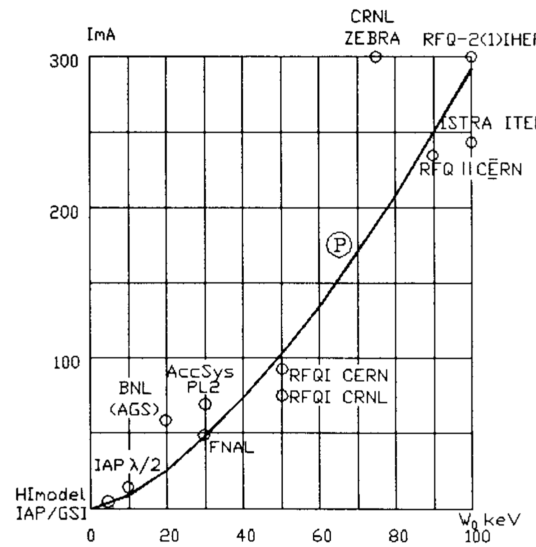


Fig.2 A current limit into RFQ

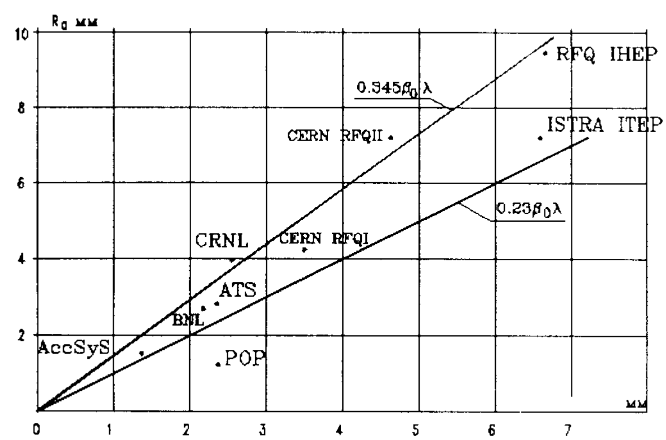


Fig.3

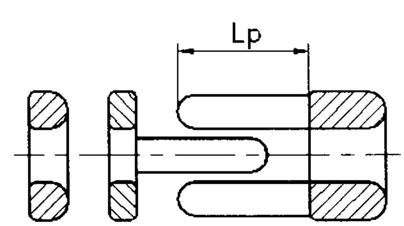
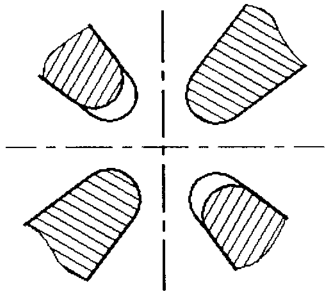


Fig.4 MPA electrodes



4V–electrodes

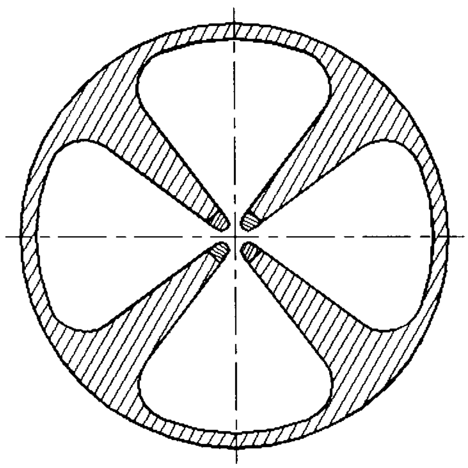
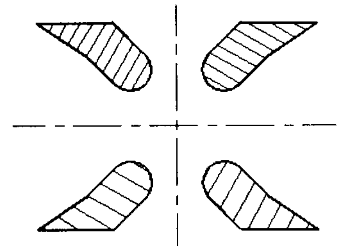


Fig.5 4V–resonator



4V–electrodes

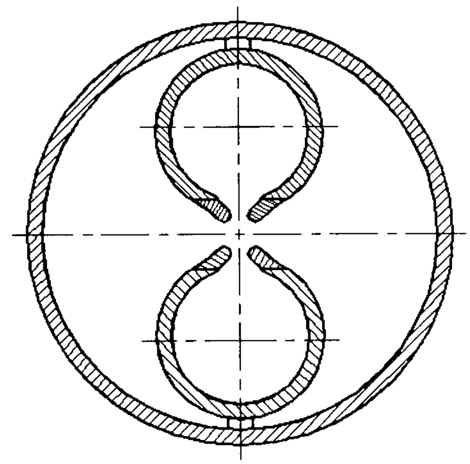


Fig.6 2H–resonator

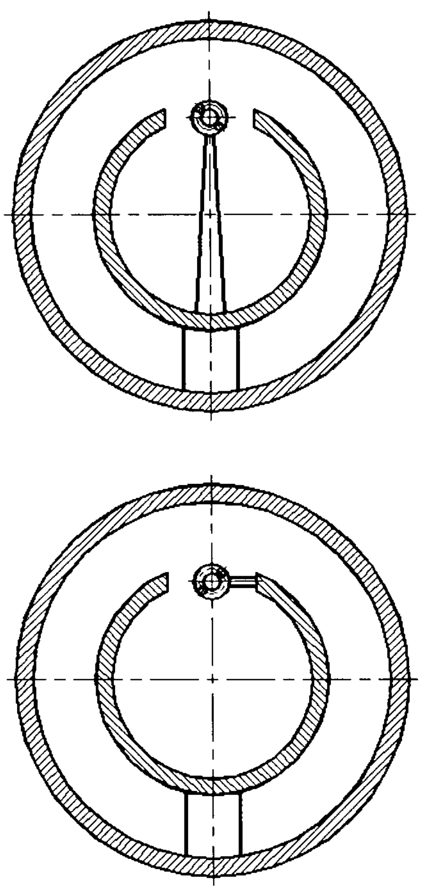


Fig.7 H–resonator

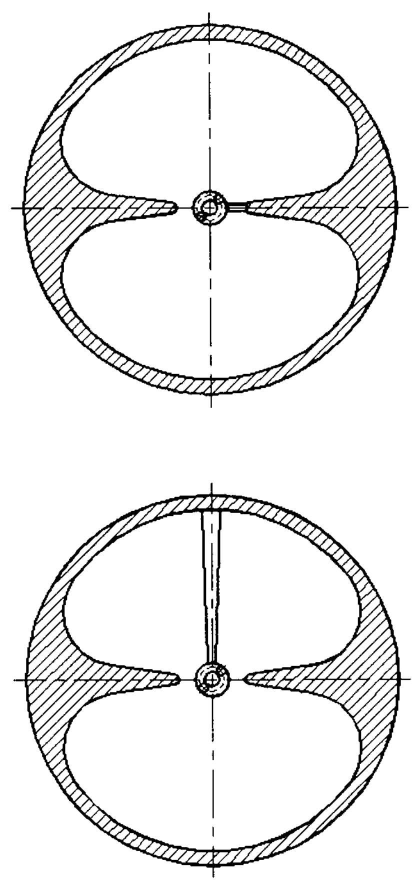


Fig.8 2C–resonator

TABLE 1
RFQ Focusing Linacs in Russia

Institute	IHEP							ITEP		ITEP INP
Installation	RFQ1	RFQ2	URAL-30	PL-1	DL-1.4	PL-35	URAL-60	ISTRA	HI	
Ion	p	p	p	p	d	p	p,H^-	p	Xe^{++}	p
Output energy Mev	1.98	1.98	30	1.0	1.4	35.8	60	3.0	0.36	0.75
Input energy Mev	0.1	0.1	1.98	0.04	0.04	0.1	0.1	0.088	0.00096	0.40
Beam current mA	300	130	100	60	50	100	120	250	10	100
Frequancy MHz	148.5	148.5	148.5	152.5	152.5	148.5	148.5	148.5	6.2	200
Vane voltage kV	167	150	300 ÷ 350	80	90	250 ÷ 610	250 ÷610	185	190	
Surface field Mv/m	27.6	22.5	38÷37	23.5	24	37	37	25		
Emittance $\pi\ mm \cdot mrad$	8	2	8	3	2	2	3			4.5
Aperture mm	9.5	6.7	9.5 ÷ 11	4.4	3.46	6.0	6.0	7.7		4.1 ÷ 6.85
Length m	3.5	4.0	27	1.96	1.96	21	30	4.9	12	1.2
Pulse length $\mu\ sec$	10	10	10	100	100	100	10			200
Repetition rate Hz	20	20	20	1	1	100	20			50
Type [illegible]ity	2H	2H	H	2H	2H	2C	2C	4V	4R	4R
Operates since	1981	1985	1981	1991	–	–	–	1982	1986	–