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A RFQ CONCEPT USING CIRCULAR RODS*

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Summary

Although the RFQ principle was suggested in 1969 already[1], a first successful test did not happen until 1980.[2] In this paper emphasis is taken on a RFQ configuration, which differs from the one used in Los Alamos however, consisting of modulated circular rods, as figs. 1 and 6 indicate. Of course the zero mode operation does not necessarily require such plain rods, profiles as investigated at Los Alamos can be used as well, the simplicity of manufacture seems evident. Considerations of rf properties and technical aspects are dealt with in another paper[3]. Here we present our way of generating the linac with respect to a maximum beam current and demonstrate the method by three examples, namely a 50 mA fusion preaccelerator for $^{133}Cs^{1+}$-ions (4.5 - 100 keV/amu, 13.5 MHz), a 390 mA proton injector linac (0.115 - 2 MeV, 100 MHz) and a study model for protons (10 - 300 keV, 108 MHz, 10 mA), being under construction in Frankfurt, which is designed for experimental tests of beam behaviour and rf investigations.

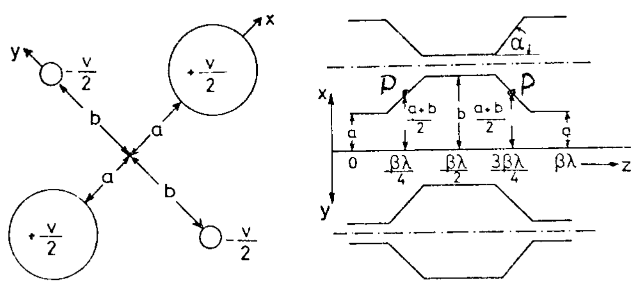

Fig. 1 Cross sections of RFQ rods
a) x-y intersection at z = 0, βλ
b) x-z and y-z intersections

Beam Dynamics and Design Considerations

The electrical potential may be represented by a Fourier expansion

$$\Phi(x,y,z,t) = \frac{V}{2}\sin(\omega t - \phi)[C_0 \frac{x^2 - y^2}{a^2} + \frac{1}{2}\sum_{M=1}^{\infty} A_{2M-1}\cos(2M-1)kz(\mathrm{ch}(2M-1)kx + \mathrm{ch}(2M-1)ky)] \quad (1)$$

where we have omitted terms with even Fourier coefficients A_{2M} in (1), thus restricting ourselves to electrode profiles uneven with respect to points P (s. fig. 1). As a consequence a simple expression for C_0 results

$$C_0 = \frac{4a^2}{(a+b)^2}\,. \quad (2)$$

In general all Fourier coefficients are related to the electrode shape represented by a, b and $\beta\lambda$ in a rather complex manner. A certain profile is characterized by the omission of all Fourier coefficients except A_1 with the consequence of losing the above symmetry, which led to (2). In this case closed expressions

$$A_1 = 2\frac{b^2 - a^2}{b^2(1 + \mathrm{ch}ka) + a^2(1 + \mathrm{ch}kb)} \quad (3)$$

$$C_0 = a^2\frac{2 + \mathrm{ch}ka - \mathrm{ch}kb}{b^2(1 + \mathrm{ch}ka) + a^2(1 + \mathrm{ch}kb)} \quad (4)$$

can be deduced from (1). This course is taken at Los Alamos, although equations (3) and (4) do not agree precisely with (5) and (6) in [4], due to slightly different boundary conditions, they correspond to a high degree in all practical cases however. From (1) and (2) conventional linear equations result for certain particle motions that are the transversal motions of synchronous particles

$$\frac{d^2 {}^x_y}{dt^2} + \frac{e}{m}\left(\pm\frac{4V\sin(\omega t - \phi_s)}{(a+b)^2} - \frac{VA_1\pi^2 f^2\sin\phi_s}{2v^2} - \frac{3QF_{^x_y}}{4\pi\varepsilon_0 a_x a_y a_u}\right){}^x_y = 0 \quad (5^a_b)$$

and the longitudinal motions of particles on the axis

$$\frac{d^2u}{dt^2} + \frac{e}{m}\left(\frac{VA_1\pi^2 f^2\sin\phi_s}{v^2} - \frac{3QF_u}{4\pi\varepsilon_0 a_x a_y a_u}\right)u = 0 \quad (5c)$$

Space charge is expressed by the usual K.V. setting[5,6] (extended to three dimensions), where the beam bunch is understood as an ellipsoid with semiaxes a_x, a_y, a_u uniformly filled with a total charge Q corresponding to the mean beam current $I = f\cdot Q$. As long as these envelope functions $a_x(t)$, $a_y(t)$, $a_u(t)$ have the linac period $1/f$, any $\beta\lambda$-section is optically matched to its predecessor. So the goal of our computations is to match the electrode profile such that this envelope period is maintained as long as possible. But this is settled by the tuneshifts μ_x, μ_y, μ_u of the motions (5a,b,c) respectively. In order to determine those tuneshifts the three equations (5a,b,c) and simultaneously the three envelope functions have to be calculated within all $\beta\lambda$-sections, after the three acceptance ellipses[7] of the first section have been taken as initial beam emittances. Computations show that matching is satisfying, when the tuneshifts μ_x (or μ_y) and μ_u are kept constant along the accelerator. For the longitudinal motion (5c) this means

$$\frac{A_1\sin\phi_s}{v^2} = \mathrm{const.} \quad (6)$$

As maximum semiaxes a_x, a_y we take the minimum aperture radius a of the linac (fig. 1), as the axial one we use an expression

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$$a_u = \frac{v}{\pi f}\sqrt{1 - \phi_s ct\phi_s} = \text{const.} \quad (7)$$

which can be derived by approximating the separatrix by an ellipse and taking its angular semiaxis[9].

We start our linac considerations in this paper with the gentle buncher section omitting the preceding shaper as well as the transverse matcher. For a more detailed discussion of these elements we refer to [4]. Usually the initial synchronous phase ϕ_0 together with the velocity v_0 are given at the input of the buncher. Further fixed data are the final synchronous phase ϕ_s and the final aperture radius a both being kept constant after gentle bunching is finished. As a first step the velocity v_S, which corresponds to ϕ_S, is calculated using (7). Now an arbitrary tuneshift $\mu_{x,0}$ not yet depressed however and Q = 0 are taken for a zero approach. A corresponding $\beta\lambda$ accelerator section for this v_S-ϕ_S pair is determined bringing about a parameter combination $A_{1,S}C_{0,S}$. Then (1) gives an acceleration parameter $A_{1,0}$ for the first buncher section with given v_0, $\phi_{S,0}$ and the condition $\mu_{x,0}$ = const. corresponds to a certain $A_{1,0}C_{0,0}$ combination. Now by switching on and increasing space charge Q stability limit is reached either axially or transversally. Since stability boundaries correspond to depressed tuneshifts with $\cos\mu_x = +1$ or $\cos\mu_u = +1$ and A_1 appears in (5a) or (5b) but with opposite sign in (5c) corresponding current limits have a scope that fig. 2 exemplarily demonstrates. Then iterating the undepressed $\mu_{x,0}$ a maximum current I_{max} as well as an optimum undepressed tuneshift with unique parameter combinations $A_{1,0}C_{0,0}$ for the first buncher section and $A_{1,S}C_{0,S}$ for the first accelerator section are obtained. Using this parameter set a "nominal" beam current of about 0.5 I_{max} is defined. By keeping the optimum undepressed tuneshift $\mu_{x,0}$ constant the buncher part is successively generated using conditions (6) and (7). Later on in that accelerator part however, where the degree of freedom in the synchronous phase is exhausted and the inner aperture is kept constant only the outer radius b is left as a free parameter. Here matching proved satisfactory, when we adjusted the

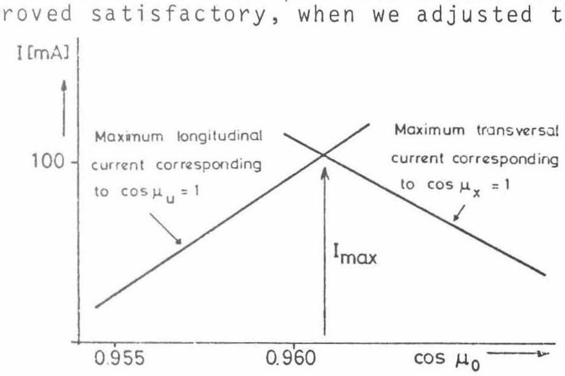

Fig. 2 Maximum axial and transversal currents leading to maximum beam current and corresponding tuneshift (linac data s. fig. 3)

outer b such that still the undepressed tuneshift $\mu_{x,0}$ was kept constant. The following examples illustrate matters.

Two linac designs we present as examples, a 50 mA $^{133}Cs^{1+}$ fusion injector and a 390 mA proton system. Fig. 3 sketches the electrode profile of a 13.5 MHz Cs sample with beam envelopes. In fig. 4 the proton injector is outlined. It should be noticed that the correct fast oscillations of the beam envelopes in figs. 3 and 4 correspond to the structure period, while the slow oscillations are either caused by a tiny mismatch frequently occuring with the sensitive K.V. model. This seems negligible however, when more realistic space charge distributions are considered and can be learned from [10], table 4, and [12], table 4, where similar linac examples are discussed.

A preliminary description of our proton study model was given in [11]. Meanwhile we inserted some modifications favouring a design principle, where not the transversal tuneshift is kept constant but the outer radius b. This makes manufacturing much easier, since any of the four rods now consists of an inner uniform copper pipe (outer diameter 6 mm) and a proper sequence of short copper cylinders (inner diameter 6 mm) being shoved and soldered on it. Along the buncher the outer diameter of these cylinders increases, while in the accelerator part the modulation remains constant. Fig. 5 sketches geometrical dimensions, beam envelopes and relevant parameters. Of course mismatch is favoured with such a design modality, as envelopes drawn in fig. 5 show. For our study purposes this can be put up with however, causing a theoretical beam current limit of about 10 mA. Fig. 6 illustrates the present status of realization. Beam performance is scheduled within the next months.

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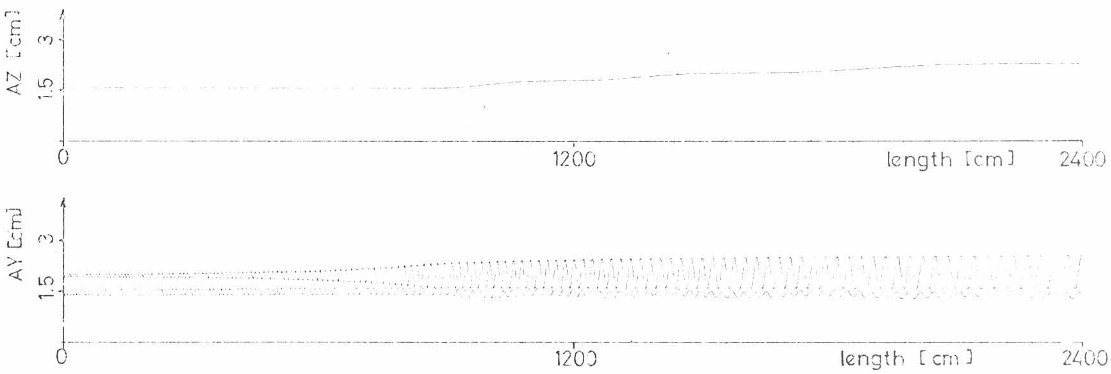

Fig. 3 Electrode profiles and beam envelopes of 0.6 - 13.3 MeV Cs Fusion injector $I_{nominal}$ = 50 mA, a = 1.6 cm, $\phi_{s0} = 30^{o}$, $\mu/\mu_0 = 0.71$, length 24 m, 150 sections, vane voltage 300 kV, 13.5 MHz, $\cos_{\mu 0} = 0.96$

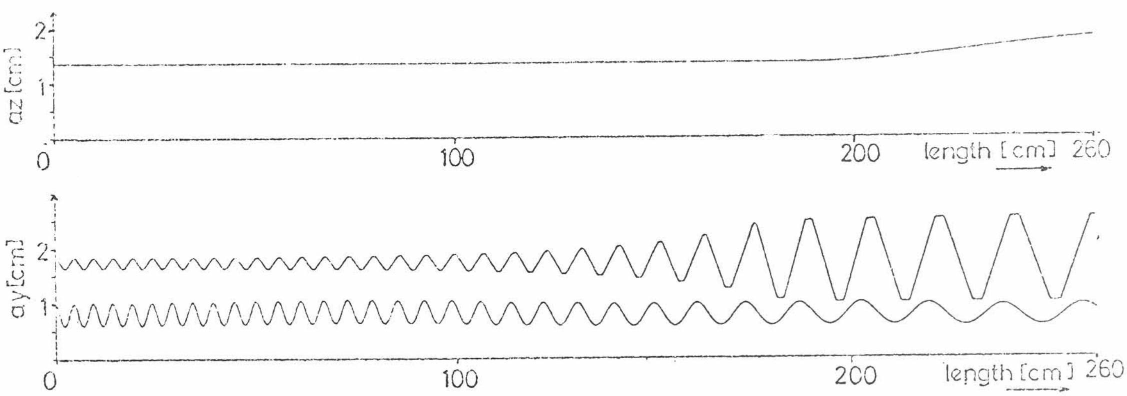

Fig. 4 Electrode profiles and beam envelopes of 0.115 - 2.28 MeV proton injector linac $I_{nominal}$ = 393 mA, a = 1 cm, $\phi_{s0} = 83^{o}$, $\phi_s = 30^{o}$, $\mu/\mu_0 = 0.72$, length 2.60 m, 31 sections, vane voltage 306 kV, 100 MHz, $\cos\mu_0 = 0.51$

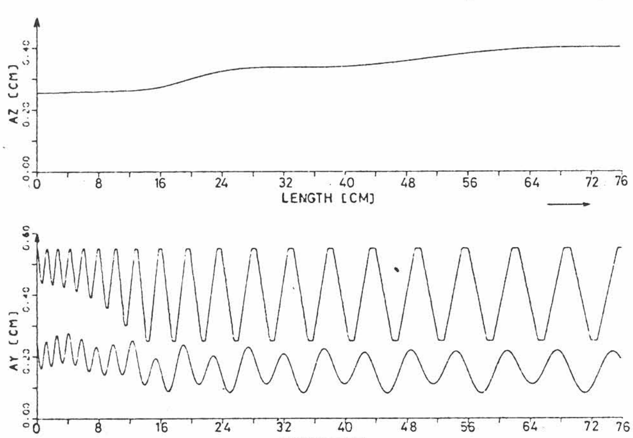

Fig. 5 Electrode profiles and beam envelopes of study model 10 - 313 keV, I = 0, a = 0.25 cm, b = 0.55 cm, $\phi_{s0} = 60^{o}$, $\phi_s = 30^{o}$, length 76 cm, 19 sections, vane voltage 25 kV

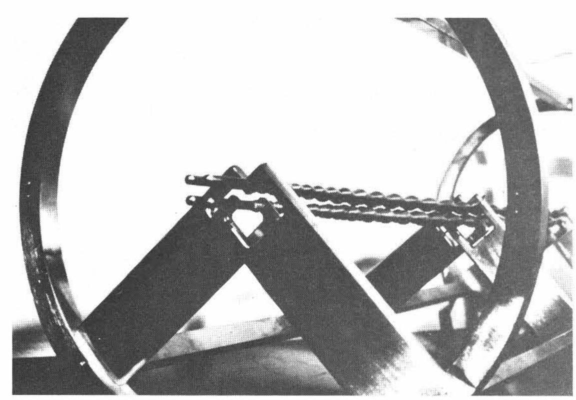

Fig. 6 Photo of zero mode RFQ structure