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Abstract

The 750 keV, 200 MHz RFQ has been chosen as a preinjector for the 50 MeV H^- - linac of the HERA project at DESY, Hamburg. It bunches and accelerates an H^- beam of 20 mA from 18 to 750 keV. The beam dynamics design of this RFQ is presented. It aims at high transmission efficiency and minimum emittance growth. The design of the beam transport lines in front and behind the RFQ are also given.

Introduction

The Radio-Frequency Quadrupole (RFQ) is a new linear accelerator structure which has the special advantage of accelerating particles of low β. (1) (2) The structure is able to accept a high current dc beam, bunch the beam adiabatically with high capture efficiency, focus the beam continuously with the full strength of the RF electric quadrupole (velocity independent), and accelerate the beam to an energy that is convenient for injection into the existent linac. Since the successful development and testing of RFQ structures at many laboratories, (2)-(11) it becomes evident that an RFQ is well suited to replace the usual preinjector of the Cockroft-Wolton type which has an ion source at the high potential terminal, leading to a large and expansive equipment and a huge building.

The 750 keV RFQ has been chosen as a preinjector for the 50 MeV proton linear accelerator (12) which is the injector of 7 GeV proton synchrotron DESY III (19). Multiturn injection into DESY III by stripping H^- ions was chosen to obtain better emittance than by one turn injection of H^+ ions, thus the RFQ will accelerate an H^- beam at a current of 20 mA. The H^- source, following the FNAL's design, will produce an 18 keV, 35 mA H^- beam. The design of 50 MeV linac is identical with the CERN Linac II. Based on these boundary conditions, the performance requirements for the RFQ are listed in table I.

Table I

Particle	H^-
Input energy	18 keV
Output energy	750 keV
Beam current	20 mA
Frequency	202.56 MHz
Beam pulse length	35 µs
Rep. rate	< 1 Hz
Normalized emittance	≤ 4 π mm-mrad (90% particles)
Energy spread	± 25 keV (90% particles)

The input energy of the RFQ was chosen at 18 keV, in order to save any other accelerating device before the RFQ. It will be indicated latter that for 20 mA beam current the RFQ can be well designed with this low injection energy.

General Description of RFQ

A 200 MHz proton RFQ normally consists of four vanes which are the electrodes. The vanes are arranged symmetrically around a central axis in z direction as shown in Fig. 1. This structure is excited with r.f. power so that adjacent vanes have equal voltage of opposite sign at a given time. The dominate resonant mode in this structure is TS_{210}-like. If the vane tip forms straight lines in longitudinal direction, then only a radial quadrupole field is excited as main component. This is a continuous alternating gradient focusing system, which is independent of particle velocity. If vane tips are periodically modulated in radius along the z-direction, an additional longitudinal field component is obtained, thus forming a focusing, bunching and accelerating structure.

The resonant frequency of the RFQ is mainly determined by the radial dimensions of the resonator. The corresponding relation is approximately (1) (14)

$$f = 30.5 \text{ MHz} \cdot \text{Meter} / R_o \qquad (1)$$

where R_o is the inner radius of the resonant cavity. For a 200 MHz cavity, R_o is about 15 cm.

For a given vane voltage V, the accelerating electric field is proportional to $^1/_\beta$ (see eq. (11)), and thus the effective shunt-impedance is proportional to $^1/_{\beta^2}$. In order to have reasonable accelerating efficiency, the output energy of a proton RFQ should be less than 2-3 MeV.

To obtain the high efficiency and the required radial focusing, the aperture of an RFQ is very small compared to the operating wave length. This small aperture causes a large capacitive loading of the structure and consequently an extreme sensitivity of the field distribution to the structure alignment. The vane tolerance normally should be kept at the level of 0.1 mm. (2) Therefore it is difficult to tune an RFQ structure to the desired accuracy in field and frequency. This high sensitivity also raises problems concerning the long term operational stability of the RFQ. To improve the tune-up process and the operational stability, the vane coupling rings (VCR) were introduced into the four vane structure (see Fig. 1).(15) Each ring connects the two opposite vanes and eliminates the near dipole modes. As a result of the strong coupling the azimuthal field balance can be ensured.

The efficiency of the uniform four vane RFQ structure, if made from copper, can be described by (1) (14)

$$Rp \cdot L = \frac{V_{eff}^{2} \cdot L}{P} = 290\ \mathrm{k\Omega \cdot m} \cdot (f/100\ \mathrm{MHz})^{-1.5} \qquad (2)$$

where Rp is the shunt-impedance, L the length, and P the power loss of the structure, excluding the power loss on the end plates. If f, V_{eff}, and L are 200 MHz, 100 kV, and 1.5 m respectively, then the structure dissipates a power of 100 kW. RF power is fed directly into the cavity via an inductive loop which is located at the center of RFQ in one of four quadrants.

Beam Optics of the RFQ

In cylindrical coordinates (r, ψ, z) the lowest-order potential given by Kapchinskij-Teplvakow (K-T) is

$$U = \frac{V}{2}\,[\,X\left(\frac{r}{a}\right)^{2}\cos 2\psi + AI_0(kr)\cos kz\,] \cdot \sin(wt+\varphi) \qquad (3)$$

where $$A = \frac{m^2 - 1}{m^2 I_0(ka) + I_0(mka)} \quad \text{(accelerating coefficient)} \qquad (4)$$

$$X = 1 - AI_0\,(ka) \quad \text{(focusing coefficient)} \qquad (5)$$

and $k = 2\pi/\beta\lambda$ the wave number; V is the potential difference between adjacent pole tips; a is the minimum aperture radius; m is the vane modulation. From (3) the electric field components are obtained:

$$E_r = -\,[\,\frac{XV}{a^2}\,r\cos 2\psi + \frac{KAV}{2}\,I_1(kr)\cos kz\,]\sin(wt+\varphi) \qquad (6)$$

$$E_\psi = \frac{XV}{a^2}\,r\sin 2\psi\,\sin(wt+\varphi) \qquad (7)$$

$$E_z = \frac{KAV}{2}\,I_0(kr)\sin kz\,\sin(wt+\varphi) \qquad (8)$$

One can find, from (3), the quantity VA is the potential difference on the axis between the beginning and the end of the unit cell (see Fig. 2) which has length of $\ell = \beta\lambda/2$. Thus the space-average longitudinal field is given by

$$E_o = 2\,AV/\beta\lambda \qquad (9)$$

The energy gain of a synchronous particle with charge e and synchronous phase φ_s passing through an unit cell is

$$\Delta W = eE_o\,T\,\ell\cos\varphi_s \qquad (10)$$

where $T = \pi/4$, the transit time factor. From (9), (10), the accelerating rate of an RFQ is obtained

$$\frac{dw}{dz} = \frac{2\,eAVT}{\beta\lambda}\cos\varphi_s \qquad (11)$$

which is proportional to AV/β.

The radial focusing force, from (6) and (7), is proportional to XV/a^2. Thus the quantities A and X are called the accelerating and foxusing coefficients respectively. They mainly depend on the vane modulation m. With increasing m, A is increased and X is decreased. To compromise the accelerating efficiency and radial focusing force, m should normally not exceed 2.

From the electric field expression (6) - (8), the longitudinal and linear radial motion equations, excluding the space charge effects, can be obtained:

$$\frac{d}{dz}(\beta^3\gamma^3\frac{d}{dz}(\Delta\varphi)) + \frac{\pi^2 e\,VA}{m_o c^2 \beta\lambda^2}(\cos\varphi - \cos\varphi_s) = 0 \qquad (12)$$

$$\frac{d^2 r}{dz^2} + (B\cos\varphi + \Delta_{rf})\,r = 0 \qquad (13)$$

where
$$B = \frac{e\lambda^2}{m_oc^2}\,\frac{XV}{a^2} \tag{14}$$

the radial focusing strength, and

$$\Delta_{rf} = \frac{\pi^2\, e\, VA \sin\varphi}{2\, m_oc^2\, \beta^2} \tag{15}$$

the usual rf defocusing strength. From (14) the radial focusing strength does not explicitly depend on z, thus for given values of a, m and β, the focusing strength is constant through an unit cell and one can keep the same focusing strength in every unit cell by changing the parameters such that XV/a^2 is constant.

the vane pole-tip shape required to generate the above electric fields is given by [2]

$$X_p^{\,2} - y_p^{\,2} = r^2 \cos 2\psi = \frac{a^2}{X}\,[1 - AI_o(kr) \cos kz\,] \tag{16}$$

in x - y transverse plane, and

$$\frac{X_p^2}{a^2} = \frac{1 - AI_o\,(kx_p) \cos kz}{1 - AI_o\,(ka)} \tag{17}$$

in x - z plane. At the middle of each cell, $z = \beta\lambda/4$, the four vanes have the property of four fold symmetry, and $x_p(z) = y_p(z) = a / X^{1/2}$. From this relation, the mean aperture radius r_o is defined as

$$r_o = {}^{a}/_{X^{1/2}} \tag{18}$$

Based on equ. (14) and (18), if one maintains B constant, then r_o is constant. Such a situation is useful to minimize variations in the vane-to-vane capacitance and to keep the pole-tips voltage distribution, $E_p = V/r_o$, flat over its entire length. It is thus convenient to choose B and r_o constant in the design of RFQ structure.

The space charge effects play an important role in the beam dynamics design of RFQ due to very low velocity (in our case, $0.006 \lesssim \beta \lesssim 0.04$). The smoothed longitudinal and radial equations of motion with linear space charge effects are presented for a well bunched beam by:

$$\frac{d^2(\Delta\varphi)}{dz^2} + k_\ell^2\,(1 - \mu_\ell)\,\Delta\varphi = 0 \tag{19}$$

$$\frac{d^2r}{dz^2} + k_r^{\,2}\,(1 - \mu_r)\, r = 0 \tag{20}$$

where μ_ℓ and μ_r are the ratios of the space charge forces to the smoothed or average restoring forces ($k_\ell^{\,2}$, $k_r^{\,2}$) in longitudinal and radial motions respectively:

$$\mu_\ell = \frac{90\ I\ (\text{amps})\ \beta^2\lambda^3 f(b/r_b)}{\pi^2 V\ (\text{volts})\ b/r_b^{\,2}\ A|\sin\varphi_s|} \tag{21}$$

$$\mu_r = \frac{45\ I\ (\text{amps})\ \lambda\ [1-f\ (b/r_b)]}{moc^2(ev)\ \beta^2\ r_b^{\,2}\ b\, k_r^{\,2}} \tag{22}$$

with $k_\ell^{\,2} = \dfrac{\pi^2\, ev\, A}{moc^2\beta^4\gamma^3\lambda^2}$, $k_r^{\,2} = \dfrac{1}{8\pi^2\beta^2\lambda^2}\,[B^2 + 8\pi^2\Delta_{rf}]$, $r_b^{\,2} = r_x \cdot r_y$,

b being the half length of bunch, $f({}^{b}/_{r_b})$ the form factor of the beam bunch which is assumed here as an uniform distribution of charge within a three-dimensional ellipsoid. The factors μ_ℓ and μ_r reduce the phase space area in longitudinal and radial motions respectively. From (19) and (20), the longitudinal and radial current limits are obtained when $\mu_\ell = 1$ and $\mu_r = 1$:

$$I_\ell = \frac{AV|\varphi_s|^3\, r_b}{120\,\lambda} \tag{23}$$

$$I_r = \frac{\beta|\varphi_s|\, r_b^2\, moc^2 [B^2 + \delta\pi^2\Delta_{rf}\,]}{720\,\pi^3\,\lambda^2\, e\,[\,1-f\,]} \tag{24}$$

with the approximation of $f({}^{b}/_{r_b}) = {}^{r_b}/_{3b}$ (in the range $0.8 < {}^{b}/_{r_b} < 5$) and $b = \frac{\beta\lambda|\varphi_s|}{2\pi}$. Both I_ℓ and I_r decreases rapidly as the beam is bunched, and they are functions of RFQ design parameters V, A, B and so on. In order to control particle losses, μ_ℓ and μ_r must be less than about 0.5. This means that one should choose the RFQ parameters such that the current limit is higher than 2-times the operating current.

Most important, concerning the space charge effects, is the fact that the coupling between longitudinal and transverse motions due to non-linear space charge force leads to a radial emittance growth (usually by a factor of 2-3) (16) which has to be controlled in the dynamics design.

Design Procedure

From the relations (3) - (10), (14), (18) and (21) - (24), which are the basis for the design procedure, one can see that all parameters are strongly dependent on each other, leading to a large inflexibility of a chosen set. If the ion species, the frequency and the input and output energies are given, then the basic parameters for the RFQ design are reduced to V, $\varphi_s(z)$, A(z) and B(z). Furthermore parameters A and B are determined when the independent functions a(z), m(z) are given.

The RFQ design should aim at obtaining high transmission efficiency, adequate radial focusing and small radial emittance growth. The well design procedure and the resulting computer code PARMTEQ were developed at LASL (2), which is now being used at most of the laboratories. In this procedure, the RFQ is devided into four sections, named Radial Matching (RM), Shaper (SH), Gentle Buncher (BG) and Accelerating (AC) sections. These sections have the following functions:

As the first section, RM matches the time independent injected dc beam into the time dependent radial acceptance of RFQ. The vane has no modulation (m = 1) in this section. By varing the vane aperture a from a large value at the beginning to a suitable one over a length of a few $\beta\lambda$, the radial focusing strength changes from almost zero at the beginning to its full value at the end of this section.

In the Gentle Buncher section, GB, to protect the beam against the strong longitudinal space charge effect during the bunching course, the charge density distribution is controlled and kept approximately constant by keeping

$$\Omega_0{}^2 = \frac{eVA\omega^2 \cdot \sin|\varphi_s|}{4\,moc^2\,\beta} = \text{const.} \qquad (25)$$

$$Z_b = \frac{\beta\lambda}{2\pi}\,\phi = \text{const.} \qquad (26)$$

where $\Omega_0{}^2$ is the small angle longitudinal oscillation frequency, Z_b is the bunch length, and ϕ is satisfied with

$$\mathrm{tg}\,\varphi_s = \frac{\sin\phi - \phi}{1 - \cos\phi} \qquad (27)$$

From (25) and (26) the functions A(β) and $\varphi_s(\beta)$ are determined. By keeping the radial focusing strength B at a suitable constant value (which is a compromise between adequate radial stability and aperture size), the three independent functions $\varphi_s(z)$, a(z) and m(z) are determined in the GB section. This K-T solution leads to a constant vane voltage V, the synchronous phase φ_s is reduced gradually from large value to the final one, the vane modulation m increases to the maximum value, and the aperture a decreases to its minimum value. At the end of the GB section, the beam is well bunched, and the beam current limit I_c is presented at this point. The values of a and m at the end of GB section can be determined beforehand by choosing the current limits, equ. (23, 24), about 2 times the operating current.

At the same time the vane voltage should be determined such that the peak surface electric field on the vane tips, $E_{s\,max}$, is at a conservative value which is lower than sparking threshold. Based on the experiment on the CERN RFQ 1 (4), this threshold value is higher than 35 MV/m for a 200 MHz cavity, which is about 2.4 times the kilpatric limit E_K. According to the computation of four vane RFQ cavity, the $E_{s\,max}$ is presented at the middle of a cell longitudinally and at some points on the pole surface near the pole tips where the distance between adjacent vanes is shortest. The ratio k of $E_{s\,max}$ to the electric field at the pole tip E_p is a function of the vane tip geometry.

Normal values are k = 1.3 - 1.6, which compromise between limited $E_{s\,max}$ and small influence of high order harmonic fields.(17) In our case $I_c = 60$ mA, $k = 1.56$, $E_{s\,max} = 1.5\,E_K = 21.9$ MV/m and $\varphi_{s\,f} = -30^0$ are chosen. Then, with equ. (23), (24) and the following two formalas:

$$r_o = \frac{e\lambda^2 E_{s\,max}}{moc^2\,B\,k} \qquad (28)$$

$$V = \frac{e\lambda^2 E^2_{s\,max}}{moc^2\,B\,k^2} \qquad (29)$$

the values of V, B, A, m, a and r_0 are determined at the end of the GB section as: $V = 70.5$ kV, $B = 6.50$, $m = 1.878$, $a = 3.5$ mm, $r_0 = 5.0$ mm.

The shaper section, SH is at the beginning of the bunching course and located in front of GB section, where the longitudinal space charge effects are not too strong, thus the longitudinal oscillation frequency can be increased gradually along the axis by starting the vane modulation ($m > 1$) and by increasing the synchronous phase from -90^0 to about -70^0. This section is used to limit the total length of the RFQ.

In the accelerating section the vane modulation and the synchronous phase are kept at their final values to obtain a high accelerating rate, which also limits the total length. The particle energy goes up from about 200 keV to 750 keV in this section.

Three computer programmes, CULI, OPTI and IMS, which were developed at Jülich,(18) are used to obtain the optimum parameters in the four sections. The program CULI finds the parameters at the end of GB section so that the radial and longotudinal current limits are both at 60 mA. The vane modulation m and the synchronous phase φ_s in the SH, GB and AC sections are determined by the programme OPTI. Finally the beam parameters at the input of RM section were calculated with the programme IMS. For the injection energy 18 keV and beam current 20 mA, the length of the RM section was set to $1\,\beta\lambda$ (2 cells), because no more improvement in the beam performance at the output of RFQ could be obtained for greater lengths.

Based on this choice of parameters in each section, the RFQ was generated by the computer code RFQGEN, and the beam motions through the entire RFQ were calculated by the tracing code RFQDYN, in which the non linear rf fields and non linear space charge forces are included. These two codes are the main components of PARMETQ program.

The resulting design parameters of the RFQ are listed in Table II. The beam performance, listed in Table III. The performance values are found to meet the requirement of the design data well, if compared to the list of Table I.

Table II RFQ Parameters

Section		RM	SH	GB	AC
Z (m)	0	0.01	0.04	0.67	1.18
Cell No.	0	2	83	113	135
φ_s (deg.)	-	-90	-68	-30	-30
m	1	1	1.18	1.88	1.88
a (mm)	20.3	5.0	4.7	3.5	3.5
r_o (mm)	20.3	5.0	5.0	5.2	5.2
B	0.4	6.5	6.5	6.5	6.1
E_o (MV/m)	0	0	0.50	2.12	1.27
W (keV)	18	18	30	212	750

Intervane voltage	70.5 kV
Max. electric field	21.9 MV/m

A high transmission efficiency (96%), small radial emittance growth (a factor of 1.4) and small energy (10.4 keV) and phase spread (22.6 deg.) for 90% particles are achieved. With low injection energy (18 keV, for saving any dc accelerating device before the RFQ) and with 70.5 kV vane voltage (so that the corresponding $E_{s\,max}$ is within very safe value), the total length of RFQ is about 1.3 m which will make it easy to fabricate and to assemble the whole RFQ structure within the required tolerance (e.g. vane fabrication tolerance ± 0.02 mm, and overall precision after assembly ± 0.1 mm). Fig. 3 shows the parameters as a function of the z axis, and Fig. 4 shows the corresponding beam envelopes in the RFQ.

Table III Beam Performance (for 90% particles)

		Input	Output
Energy (keV)		18	750
Normal current (mA)		20	19
Current limit (mA)			60
Normalized emittance	(π mm - mrad)	0.7	1.0
Normalized rms emittance	(π mm - mrad)	0.17	0.22
Beam envelope	$\hat{x}$ (mm)	1.8	2.1
	$\hat{y}$ (mm)	1.8	1.8
Ellipses parameters	α_x	0.569	2.41
	β_x (cm)	2.06	15.7
	α_y	0.569	-1.46
	β_y (cm)	2.06	12.0
Normalized long. rms emittance (π deg-keV)		0	50
Energy spread (keV)		0	10.4
Phase spread (deg.)		360	22.6

Beam Transport to RFQ (LEBT)

The RFQ preaccelerator requires a convergent input beam with $\hat{x} = \hat{y} = 0.18$ cm and $\hat{x}' = \hat{y}' = 102$ mrad. The matching from the H^- source to the RFQ is done by two pulsed solenoid magnets placed in a short low energy (18 keV) beam transport line.

Based on the beam measurement at the H^- source $^{(19)}$, the corresponding emittance parameters are deduced at the input value of the LEBT:

$$\alpha_i = -1.40, \quad \beta_i = 34.9 \text{ cm}, \quad E_{i,n} \lesssim 1\ \pi \text{ mm-mrad}$$

and the required emittance parameters at the output of LEBT (i, e, at the input of RFQ) are given by the programme IMS:

$$\alpha_f = 0.569, \quad \beta_f = 2.06 \text{ cm}.$$

We propose to use the same solenoids as constructed at CERN for their 50 keV-LEBT line of RFQ 1, which has 17 cm physical and 12 cm effective length and an aperture of 4.5 cm. It can be operated in a pulsed mode up to 1 Tesla central field. The envelope for a matched beam of 20 mA is calculated with the programme RFQLEB as shown in Fig. 5, curve a. Also a completely neutralized beam can be matched to the RFQ input, just by changing the solenoid magnetic field settings (curve b). The required magnetic fields are about 0.5 Tesla. The total length and the position of the solenoids is optimized to leave space for accomodating a beam toroid, a profile probe, a pump flange and a beam stop integrated in a vacuum valve. In order to study and control beam neutralization a gas inlet will be installed on the LEBT line.

Beam Transport to the Alvarez Linac

The RFQ is followed by a short ($2\beta\lambda$) line which allows the accomodation of a beam toroid and a vacuum valve. The transverse matching into the Alvarez structure is performed by the first four quadrupoles of tank I. Fig. 6 shows the calculated beam envelopes $\hat{x}$, $\hat{y}$ between the RFQ output and drift tube No. 5 in tank I. They do not exceed 0.4 cm, while the bore radius of drift tubes is 1.0 cm. In the longitudinal phase space, the energy spread and phase spread at the first accelerating gap in tank I are 13.5 keV and 25.1^0 for 90% of particles in the 20 mA beam. These spreads lie within the longitudinal acceptance.

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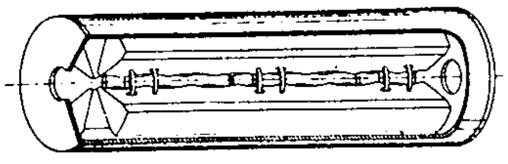

Fig. 1 Four Vane RFQ with VCR's

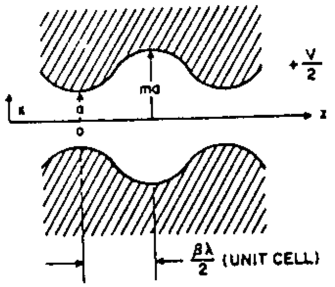

Fig. 2. RFQ pole-tip geometry.

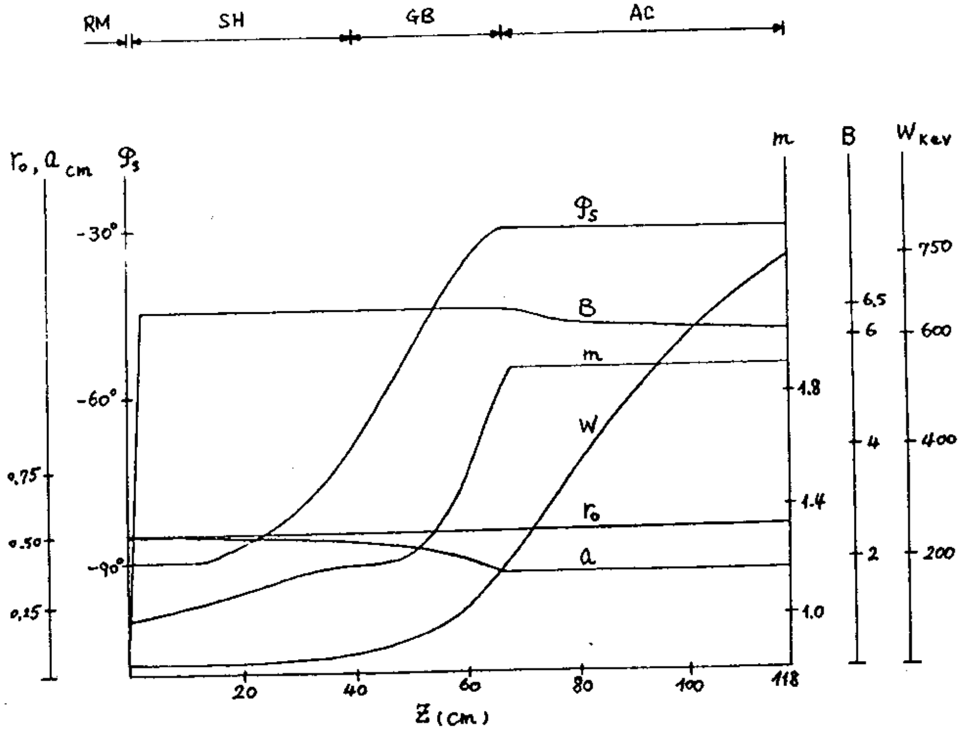

Fig. 3 Functions $B(z)$, $\varphi_s(z)$, $W(z)$, $m(z)$, $r_0(z)$, $a(z)$

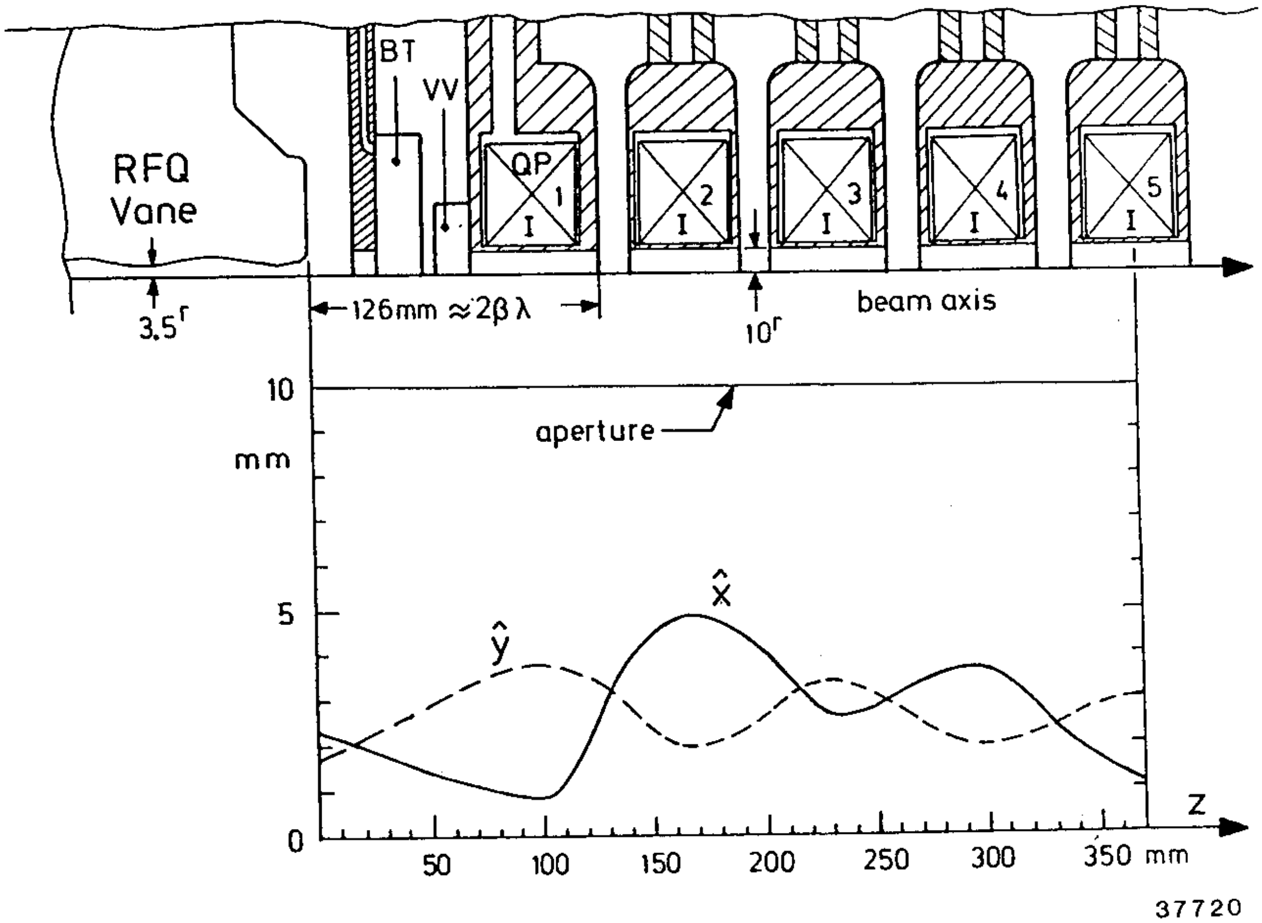

Fig. 6 Beam Envelopes from RFQ to QP No. 5

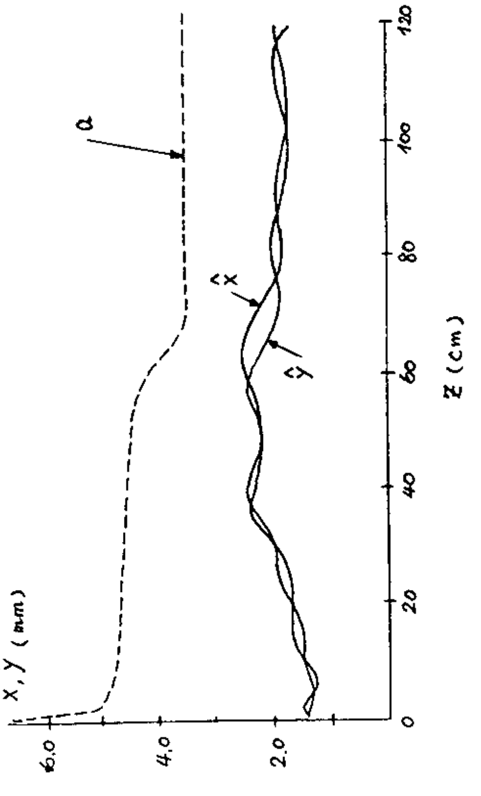

Fig. 4 x̂, ŷ —— Beam Envelopes (90% Particles)
a —— Min. aperture radius

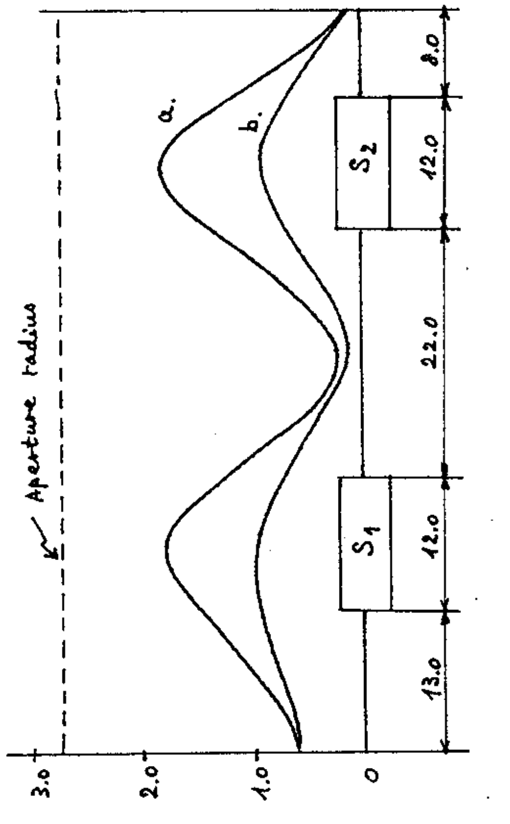

Fig. 5 Matched Beam Envelopes in LEBT Line
a) I = 20 mA, b) I = 0 mA.