SELF FOCUSING IN HEAVY ION LINACS

(Autofocalisation dans les accélérateurs linéaires à ions lourds*)

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Sommaire

La focalisation des premières sections des accélérateurs linéaires à ions lourds peut être obtenue sans l'aide de grilles ou de quadrupoles magnétiques, en utilisant des tubes de glissement dont les extrémités ont des formes appropriées. Nous étudions théoriquement le mouvement des ions dans une structure dont les tubes de glissement dont prolongés par deux "doigts" diamétralement opposés. Nous montrons ainsi qu'il est possible d'assurer simultanément la stabilité axiale et la stabilité radiale du faisceau. Nous avons mesuré le spectre d'énergie et le rendement en courant de cette nouvelle structure en utilisant un modèle à basse énergie (200 keV). Les résultats sont très intéressants : le rendement en courant est de 20 % après 21 tubes de glissement, et il dépasse 60 % lorsqu'on utilise un "rassembleur". Ces résultats sont en bon accord avec la théorie et montrent qu'un accélérateur autofocalisé peut être réalisé par cette méthode . On donne ensuite les résultats théoriques relatifs à une machine "en vraie grandeur" (injecteur du cyclotron à énergie variable d'Orsay) : tensions de claquage, trajectoires, acceptance. En conclusion cette méthode présente des caractéristiques très intéressantes, et peut être employée pour réaliser les premières sections des accélérateurs à ions lourds.

Abstract

The focusing of the first sections of heavy ion linear accelerators may be achieved without the use of grids or magnetic quadrupoles by employing conveniently ended drift tubes. The ion motion is theoretically studied in a structure using drift tubes which are lengthened by two diametrically opposite "fingers". We show that it is possible to ensure simultaneously radial and axial stabilities of the beam . Using a low energy model (200 keV) energy spectrum and current yield of this new structure have been measured. Experimental results are very interesting : current yield is as high as 20 %, for a 21 drift tubes linac, and it rises above 60 % by using a bunching device. These results are in good agreement with the theory, and the construction of self focused linacs seems to be possible with this method. Theoretical results concerning breakdown voltages, trajectories, acceptance, obtained in an real case (injector of the variable energy cyclotron in Orsay) are given. We conclude that this new method has many attractive features and may be employed successfully to design the first sections of heavy ion linacs.

Introduction

The problem of focusing of heavy ion linacs has been yet solved by the use of grids fitted at the entrance of the drift tubes. This method, having a rather poor efficiency, soon becomes inadequate if high current beams have to be accelerated because of the excessive heating of the grids.

We are studying from a theoretical point of view the quadrupole self focusing method which consists in modifying the shape of the drift tubes ends. These now have the form of electric quadrupoles directly supplied by the R.F. field itself. The geometry we are speaking about may be realised with drift tubes lengthened by two diametrically opposite "fingers" (fig. 1). The calculation of many trajectories in such a structure shows us that it is possible to simultaneously ensure both radial and axial stabilities of the ion beam.

This new focusing method has been experimented on a low energy model of the Sloan-Lawrence type. In fact the current yield of a classical machine (without any focusing device) and that of the self focused structure have been compared in order to complete our theoretical investigations.

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1. Trajectories Calculation

a) - Représentation of the field in two successive gaps.

According to the Laplace's equation (valid for low frequencies used for heavy ion linacs), the potential function $V(r,\theta,z)$ may be written as a double Fourier's series expansion :

$$V(r,z,\theta)=\sum_m\sum_n A_{mn}\frac{I_n\left(\frac{m\pi r}{L}\right)}{I_n\left(\frac{m\pi a}{L}\right)}\cos\frac{m\pi z}{L}\cos n\theta$$

Oz is the axis of the accelerator, r is the distance from the axis and θ the azimuthal angle.

L is the length and $2a$ is the interior diameter of one drift tube, m,n are integers, and I_n is the modified Bessel function of the n^{th} order.

The coefficients A_{mn} depend on the shape of the potential function on the surface of the cylinder $r = a$.

We assume the potential function on the surface $r = a$ to have the shape indicated on Fig. 2. This representation seems to be rather accurate if "fingers" are longer than gaps. On the contrary, if the length of the gap is not very different from the length of the finger an experimental checking is necessary. Electrolytic tank provides an accurate control which shows that the assumed function and the real one have the same form.

The "fingers" and the drift tube bore have the same diameter in order to have very little high order terms in the r expansion (analogy with an electrostatic quadrupole, in which the ideal hyperbolic cross-section of electrodes is replaced by a circular one).

The coefficients A_{mn} may be obtained by expanding the function shown in Fig. 2 in a double Fourier's series. One obtains :

$$A'_{10}=\frac{A_{10}}{V_m}=\frac{2}{\pi}\,\frac{\sin\frac{\pi}{2}\frac{g}{L}}{\frac{\pi}{2}\frac{g}{L}}\cos\frac{\pi h}{L}$$

$$A'_{02}=\frac{A_{02}}{V_m}=\frac{h}{L}$$

$$A'_{22}=\frac{A_{22}}{V_m}=-\frac{1}{\pi}\,\frac{\sin\frac{\pi g}{L}}{\frac{\pi g}{L}}\sin\frac{2\pi h}{L}$$

V_m is the potential across the gap ;

g and h are defined on Fig. 1.

b) - Calculation of the elementary impulses in each gap.

We assume that every gap is characterized by two radial impulses $\Delta\dot r(\theta=0)$ and $\Delta\dot r(\theta=90°)$ defined in the two planes of quadrupolar symmetry. The axial motion is also defined by the two impulses $\Delta\dot\varepsilon(\theta=0)$ and $\Delta\dot\varepsilon(\theta=90°)$; ε is the abscissa shift ($\varepsilon = z-z_s$, z_s is the abscissa of the synchronous particle).

The radial equation of motion :

$$m\ddot r = e\,E_r(z,r)\sin(\omega t+\phi_o)$$

may be expanded in a double series in r and ε :

$$m\ddot r = e\sin(\omega t+\phi_o)\left[r\frac{\partial E_r}{\partial r}+\varepsilon\frac{\partial E_r}{\partial z}+\frac{r^2}{2}\frac{\partial^2E_r}{\partial r^2}+\frac{\varepsilon^2}{2}\frac{\partial^2E_r}{\partial z^2}+\varepsilon r\frac{\partial^2E_r}{\partial r\,\partial z}+\dots\right]_{\substack{r=0\\ z=z_s}}$$

Integrating on the length of one drift tube (half period of the R.F. field) and assuming the quantities r and ε varying slightly in this interval (thin-lens approximation), one gets the radial impulse $\Delta\dot r$.

The quantities $\partial E_r/\partial r$, $\partial E_r/\partial z$ .... are obtained in the form of a double Fourier's expansion. For example :

$$\frac{\partial E_r}{\partial r}=-\sum_m\sum_n A_{mn}\frac{I''_n\left(\frac{m\pi r}{L}\right)}{I_n\left(\frac{m\pi a}{L}\right)}\frac{m^2\pi^2}{L^2}\cos\frac{m\pi z}{L}$$

According to the properties of the Bessel functions I_n, their successive derivatives and to the symmetries of the function $E(r,z)$, one shows that the only terms which do not vanish are obtained for $n=0$ and $n=2$.

Thus :

$$\Delta\dot r=\frac{e}{m}r\left[\int_0^{T/2}\sin(\omega t+\phi_o)\frac{\partial E_r}{\partial r}dt+\varepsilon\int_0^{T/2}\sin(\omega t+\phi_o)\frac{\partial^2E_r}{\partial r\,\partial z}dt\right]$$

(T is the period of the R.F. field)

The radial impulse $\Delta\dot r$ is composed of two separate terms P_o and P_2 obtained respectively for $n=0$ (rotational symmetry) and $n=2$ (quadrupolar symmetry). The former P_o may be easily calculated, according to the orthogonal properties of the trigonometric functions. One finds that the $m=1$ term only remains and one finally gets :

$$P_0 = -\frac{e}{m} r \sin(\phi_0 + \Delta\phi) \frac{\pi}{\omega} \frac{\pi^2}{L^2} A_{10} \frac{1}{I_0(\pi a/L)}$$

P_0 is the classical defocusing impulse due to the transit time effect. The latter term P_2 is obtained by a different way : in the interval (0-T/2) we have expanded in a Fourier's series the expression sin ω t :

$$\sin \omega t = \frac{2}{\pi}\left(1 - \frac{2}{3}\cos\omega t - \frac{2}{15}\cos 4\omega t \ldots\right)$$

Thus P_2 has the form on an expansion the terms of which rapidly decrease. Taking account of the two first terms, one gets finally :

$$P_2 = \pm \frac{e}{m} r \cos(\phi_0 + \Delta\phi) \frac{4}{a^2\omega}\left(A_{02} - \frac{A_{22}}{3}\right)$$

Rewriting P_0 and P_2, it follows : (the time unit is here T/2)

$$\frac{\Delta r'}{r} = \left\{ - \sin\phi_0 A'_{10} \frac{\pi^2}{8} \frac{V_m}{V} \pm \cos\phi_0 \frac{4\pi}{\omega^2 a^2} \frac{e}{m} V_m \left(A'_{02} - \frac{A'_{22}}{3}\right)\right.$$

$$\left. + \frac{\varepsilon}{L}\left(\cos\phi_0 A'_{10} \frac{V_m}{V} \frac{\pi^3}{8} \pm \sin\phi_0 \frac{4\pi^2}{\omega^2 a^2} \frac{e}{m} V_m \left(A'_{02} - \frac{A'_{22}}{3}\right)\right)\right\}$$

eV in the mean energy of the particle crossing the gap.

The defocusing impulses P_0 decrease as V_m/V and the quadrupolar ones P_2 may be held constant all along the accelerator (Analogy with a magnetic quadrupole focused accelerator). Even at the beginning of the accelerator the condition $P_2 \gg P_0$ may be easily satisfied (for instance by choosing the following numerical values of parameters : 9/L=.25 g = 2h , V_m/V =.5) and it seems possible to ensure the beam stability all along the structure.

The calculation of axial motion is made in the same way. The axial impulse $\Delta\varepsilon$ is composed of two terms : the circular term and the quadrupolar term, but one shows that the former is the most important (the mechanism of axial bunching is not very altered by the presence of "fingers" at the end of the drift tubes).

Calculation of complete trajectories in a real accelerator has been made with the aid of an electronic digital computer by using the previous expressions of $\Delta\varepsilon$ and $\Delta\dot{r}$. The results show that a complete stability of the beam may be achieved by this method.

2. The 200 keV model

According to the previous results a low energy accelerator model has been constructed. He^+ ions are accelerated from the 15 keV injection energy to an output energy of 200 keV. The structure, of the Sloan-Lawrence type, is composed of 21 drift tubes whose lengths and positions are adjustable. Operating frequency is 20 Mc/s and the entire length of the machine is 1.15 m, the first drift tube having 23.08 mm long, the last having 80.67 mm. The bore diameter is 10 mm and the injection aperture is 6 mm in order to allow an expansion of the radial size of the beam (as it happens in every quadrupole system). 9/L and 9/h ratios have the respective values .25 and 2.

The injection apparatus consists of a standard "duoplasmatron" ion source followed by an extraction electrode. The beam is then focused by an electrostatic lens and possibly bunched before entering the injection pupil of the accelerator.

The apparatus is designed to measure the current yield of various structures. Two movable Faraday cups one at the entrance of the structure, one at the exit are used to achieve the input and output current measurements. Arrangements are made to avoid the mistaking influence of secondary electrons.

a) - Current yield.

We have studied the current yield of the self focusing accelerating structure in terms of the R.F. accelerating voltage. The curve is displayed on an oscilloscope (fig. 3) by amplitude modulating the R.F. oscillator. For low values of R.F. voltage there is no accelerating mechanism and then no synchronous particle. Thus the output current is null. When the synchronous phase ϕ_0 is equal to zero the output current appears and becomes greater and greater as the phase acceptance (approximately 3 ϕ_0) does. In case of larger synchronous phase angles the defocusing effect of circular impulses P_0 (proportional to sin ϕ_0) becomes important and the output current decreases. Photograph of Fig. 3 shows the variation of the output current with respect to the R.F. accelerating voltage. Input current is kept constant at a value of 200 µA. The optimum yield of this structure is equal to 20 % as it is shown by the oscilloscope picture.

A similar structure (21 drift tubes, input 15 keV, output 200 keV) without any focusing device (cylindrical drift tubes with plane ends) has been tested. We have found approximately 2-4% for the yield value. This result demonstrates the very interesting properties of a self focused linac.

According to the following measurements we have found the optimum value of ϕ_0 to be equal to -26°. Thus the order of magnitude of the phase acceptance (3 ϕ_0) is 78°. From this value and the optimum current yield one shows that it is only the axial motion which limits the output beam current. We may notice that our model simulates high current accelerators in which space charge phenomena can occur.

b) - Bunching operation.

The operation of our linac completed by a buncher seems to be very interesting because the current yield is hardly dependent on the radial motion. The buncher device is a single gritted drift tube situated 30 cm from the input aperture and supplied by a R.F. voltage. This latter and the main R.F. field are synchronous. Amplitude and phase of the buncher voltage may be adjusted. The own current transmission yield of the buncher is only 66% (when the linac is at optimum operation) because of the unfavourable influence of the bunching field on the radial motion of the beam before entering the accelerator. Fig. 4 shows the buncher influence : the current yield may be magnified about 3 times (55%) . Taking into account the own buncher transmission the current yield of the linac structure reaches near 80 %, which is a very noticeable value.

c) - Output energy spectrum.

An electrostatic energy analyser has given us the possibility of studying the output energy spectrum. We have compared the spectra obtained in the case of a classical drift tube machine (without any focusing device) and in the case of our own self focused linac. In the latter case one sharp peak (width about 10 keV) has only been found at the calculated energy. On the contrary, in the case of a classical linac many different accelerating processes can occur and the output spectrum is more complicated : one finds, in addition to the 200 keV peak many other discrete peaks at lower energies.

d) - Output bunch measurements.

These measurements have been achieved with the aid of an original and very simple apparatus. The primary ion beam falls on an aluminium target which emits secondary electrons. These are captured by an electrode placed in front of the target and supplied by a R.F. voltage. This voltage, at 20 Mc/s frequency has a variable phase compared to the main R.F. accelerating field in order to achieve a synchronous detection of the secondary electron beam.

Photograph of Fig. 5 shows the electron current (which is proportional to the primary ion bunch intensity) and the sinusoïdal reference voltage. From this we can measure the phase shift between the ion bunch and the crest of the wave. We find the value -26° for the optimum output current.

3. A real case : The injection linac for the variable energy cyclotron in Orsay

List of parameters of the heavy ion linac planned at the cyclotron department of the Institut du Radium in Orsay is given below :

Structure : Sloan-Lawrence

e/m = 1 to .125
output energy : 1 MeV/nucleon
Frequency : 20-25 Mc/s
R.F. voltage across gaps: 100-400 kV
Maximum injection voltage : 150 kV
Maximum electric field admissible in any point : 100 kV/cm
Bore diameter of drift tubes : 2 - 4 cm
Total length : 9 m

We suggest to transpose to this accelerator the previous results concerning the self focusing structures. An important problem which has been hitherto avoided is the breakdown voltage in the gaps.

a) - An estimation of the maximum electric field in one gap.

The calculation of the exact field mapping in one gap fitted with "fingers" seems to be rather difficult. But it is not necessary to know the entire field repartition : we can notice that the maximum field value certainly occurs on the ends of the fingers (We give to them a spherical shape). As a first approximation we can assume that breakdown, if it occurs, would take place between the ends of two consecutive "fingers". Thus it seems reasonable to obtain the maximum electric field in one gap by calculating the field between two spherical electrodes supplied by the potentials + $V_m/2$ and $-V_m/2$. This problem is very simple : the field expression is obtained by the classical method of charge images. As we have done for the model we choose the following values : $g/L = .25$, $g/h = 2$. Thus one finds :

$$E_m = 1.1\ V_m/a$$

E_m is the maximum electric field.

b) - Parameters of the structure

The bore radius of drift tubes being limited, the restrictive condition upon the maximum electric field implicates a restrictive condition upon the maximum voltage V_m. One finds approximately $V_m < 200$ keV. According to the variation of V_m (100 kV $< V_m <$ 400 kV) the machine has to be separated in two sections, the former (100 kV $< V_m <$ 200 kV) being self focused and the latter ($V_m <$ 200 kV) being focused by any conventional device (i.e. magnetic quadrupoles).

We assume the maximum electric field to be constant in every gap except for the first four gaps in which the field is lower. Owing to the shape of the "fingers", the condition $a < L/4$ always must be satisfied (if not the spherical end of the finger would be truncated). We assume that V_m is varying linearly with respect to the number of the gap and the synchronous phase being -26° as in our model. We are now able to calculate successive lengths of the drift tubes by the following relations :

$$\Delta W = e \cos \phi_0 \, V_m \frac{\sin \pi g/2L}{\pi g/2L} \frac{\cos \pi h/L}{I_0(\pi a/L)}$$

$$L = \beta \lambda/2$$

Fig. 6 shows the calculated parameters of this structure. The energy gain is given in the case of acceleration of Ne^{++} ions (e/m = .1). We notice that the total length of this part of the machine is not very different from the length of a machine focused with magnetic quadrupoles. The mean accelerating field is 1.1 MV/m.

c) - Acceptance

We have calculated many trajectories through this first section of the machine with respect to the injection parameters : radius r and phase shift $\Delta\varphi$. Fig. 7 shows two typical trajectories. These are useful only if the radius r is always lower than the bore radius a, and if the phase shift does not become too large ($\Delta\varphi < 90°$ for example).

For each quadrupole symmetry plane, one finds an acceptance area in the $(r, \Delta\varphi)_{inj}$ plane. The important coupling terms between axial and radial motions give an asymmetric shape to the acceptance diagram (Fig. 8). If the injection aperture is equal to the interior diameter of the first drift tube (2.5cm) the calculated current transmission yield would be about 13 % (without any bunching device).

At the exit of the first section, the magnetic quadrupole focusing is rather easy to improve. We have calculated the minimum field gradient (after Teng) and have found 6.1 T/m (610 G/cm). The first quadrupole of this second section has 11.5 cm long, and we think that no important technological difficulty will arise in this section.

Conclusion

We have first shown theoretically and then by experiment on a low energy model that it is possible to achieve simultaneously the radial and the axial stabilities of the ion beam. We think that this is the first experimental study of self focusing in heavy ion linacs. Furthermore we have calculated a real machine and shown that this new structure is able to compete with grid focused machines, especially for high current accelerators.

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DISCUSSION

D. BOUSSARD, Orsay

SLUYTERS, BNL: How far is this system practical for different machines and different intensities? You have to calculate your quadrupole shapes for each intensity.

BOUSSARD: This system is a low-intensity accelerator, but the injection voltage is quite small. If I transpose the intensity which I have in my model to a real machine--for instance, in the Manchester machine--the intensity corresponds to about 10 mA (injection intensity), which is not very small.

SLUYTERS: So the design is for a certain intensity, which remains a rather inflexible solution.

BOUSSARD: I think that the order of magnitude of injected currents in a heavy-ion machine is rather small, and space charge effects are not taken into account in the trajectories calculations.

OHNUMA, Yale: I think my question is somewhat related to the first question. One advantage of a quadrupole focusing system, I believe, is its flexibility. If required, you can change the polarities and you can change the field gradient. Generally speaking, a real machine never works like a designed machine. What kind of a flexibility can you introduce in this focusing system?

BOUSSARD: I think that self-focused machines are not to be compared with magnetic quadrupole focused machines, but with grid-focused machines, in which there is obviously no flexibility.

STADLER, Heidelberg: What is acceptance of your accelerator at the input?

BOUSSARD: I have calculated many trajectories to determine the acceptance. Because the radial and axial motions are very much coupled, the acceptance depends simultaneously on the radial dimensions and axial position. The diagram we see is the projection of the six-dimension acceptance diagram on the $(r, \Delta\phi)$ plane. The phase acceptance here is about 80°, for the optimum synchronous phase which we have found, -26°. The shape of the diagram is clearly asymmetric because of the important coupling terms between the two axial and radial motions. For the other plane of symmetry we find another diagram like this.

SEPTIER, Orsay: In answer to the preceding question, I want to mention the following point: It seems that such a structure is the one most practical for heavy ions. For very heavy ions the drift-tube lengths in the first section are very short, and it seems very difficult to put magnetic quadrupole in the tubes. Another possibility is to focus by grids. In order to compare the performance of both focusing systems, our system is now tested with grids. The transition factor is only 10-12% with grids, compared to 20% with the self-focused accelerator.

BOUSSARD: The output spectrum is more complicated in the case of a grid-focused machine and contains many peaks at various energies.

VAN STEENBERGEN, BNL: With relationship to the fixed electrostatic quadrupole focusing as discussed here, I would like to mention that at BNL, similar approaches have been explored with respect to magnetic quadrupole focusing in the BNL linac. Dr. Blewett and others have investigated the possibility of permanent magnetic quadrupoles. This was never executed. At a later stage, however, we studied the possibility of operating the BNL linac in a practical fashion by having only a very limited degree of quadrupole focusing adjustment. It appeared quite practical, instead of having 64 quadrupole pair adjustments, to fix approximately 60 of the quadrupole pair current values, keeping only the remaining four adjustable. Therefore, possibly fixed electrostatic quadrupole focusing, complimented by adjustable magnetic quadrupole focusing in small sections, might provide a practical approach to proton-linac transverse focusing at somewhat higher beam currents than you referred to.

STADLER: Can you tell us something about the radial acceptance?

BOUSSARD: Radial acceptance is defined by the fact that radial amplitudes have to be less than the drift-tube bore. We have found that with a 10-mm drift-tube bore and an injection aperture of 6 mm, there are almost no radial losses of particles. With these parameters the entire current is transmitted, and the ultimate yield is 20%. If we inject the input current in a diameter of 10 mm, for instance, the output yield current falls to 13%, without the bunching.

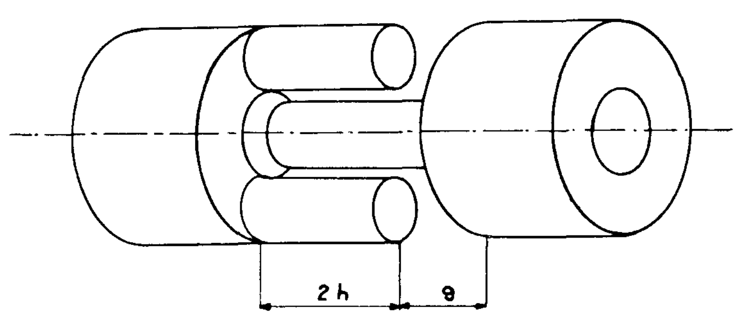

Fig. 1. Drift tubes lengthened with "fingers".

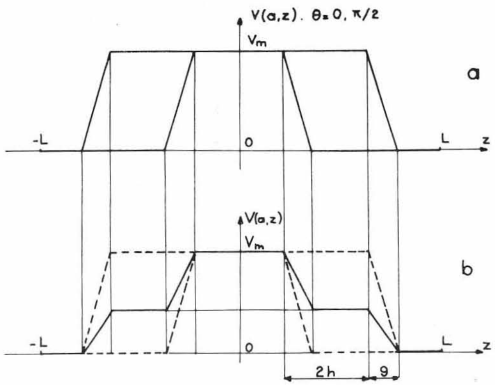

Fig. 2. Potential function on the surfact r = a. (a) $\Theta = 0$ and $\Theta = \pi/2$ (quadrupolar symmetry planes); (b) any value of Θ.

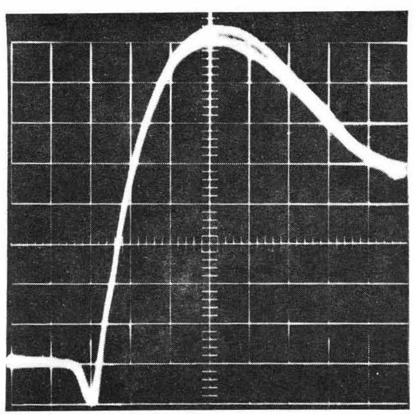

Fig. 3. Output current vs RF v voltage. (Input current: 200 μA. 1 division represents 5 μA).

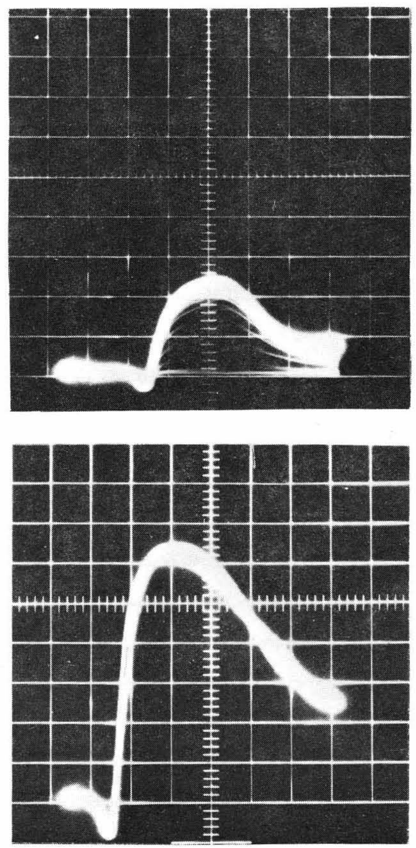

Fig. 4. The buncher effect (Input current 120 μA, 1 division = 10 μA): (a) without buncher; (b) buncher at optimum operation.

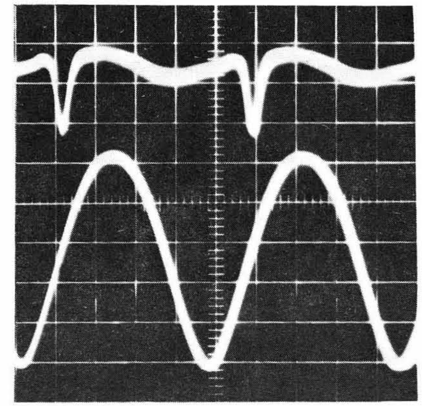

Fig. 5. Synchronous phase measurement: secondary electron peaks and the reference RF voltage.

Tube Number	Vm (kV)	a (cm)	L (cm)	Energy (keV)
1	50	1,25	4,82	185
2	100	1,25	5,65	255
3	106,6	1,25	6,47	333
4	113,3	1,25	7,23	417
5	120	1,32	8	508
6	126,6	1,39	8,7	605
7	133,3	1,47	9,4	707
8	140	1,54	10,1	815
9	146,6	1,61	10,7	928
10	153,3	1,69	11,5	1046
11	160	1,76	12,1	1170
12	166,6	1,83	12,75	1299
13	173,3	1,91	13,4	1432
14	180	1,98	14	1572
15	186,6	2,05	14,65	1717
16	193,3	2,13	15,3	1867
17	200	2,2	15,9	2023

Ion : Ne^{++}
Injection voltage : 150 kV
Output energy : 2.023MeV
Total length: 180,67 cm

Fig. 6. Calculated parameters of the proposed accelerator.

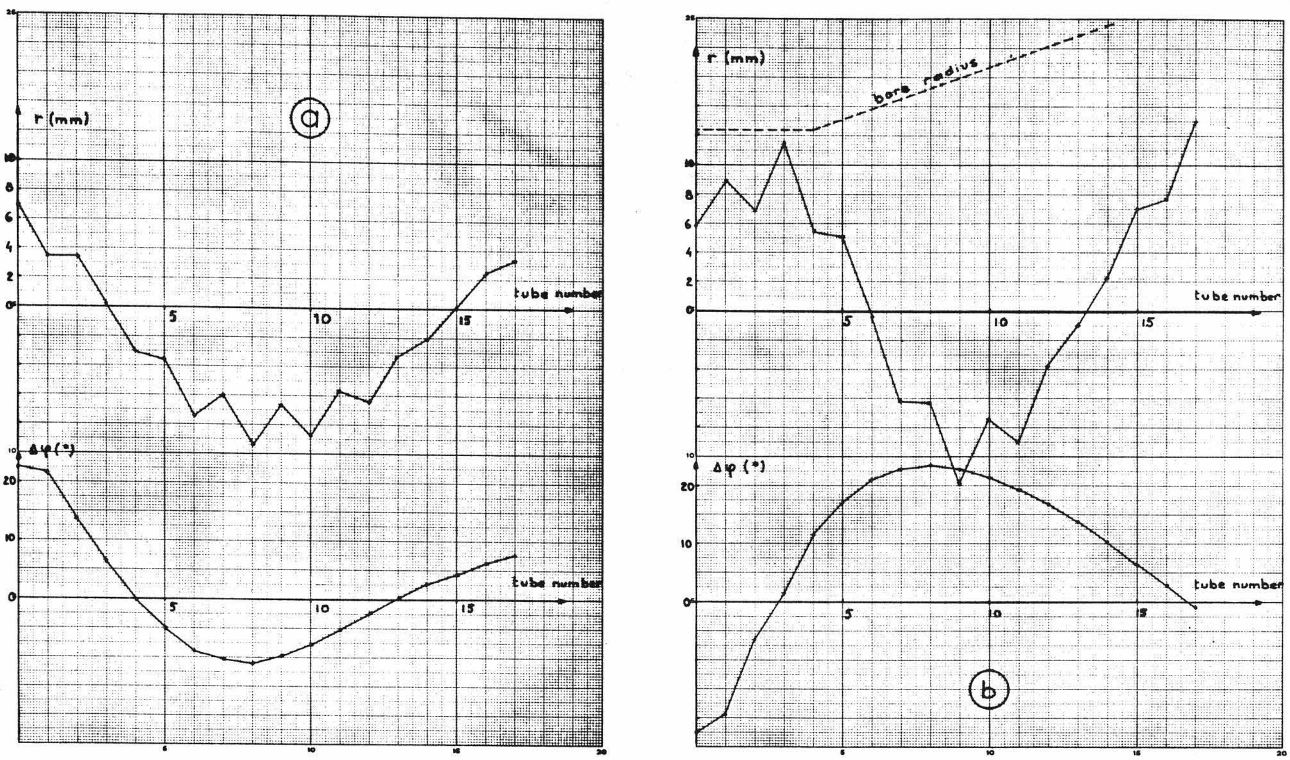

Fig. 7. Typical trajectories (radial motion and axial motion): (a) the first gap is focusing; (b) the first gap is defocusing.

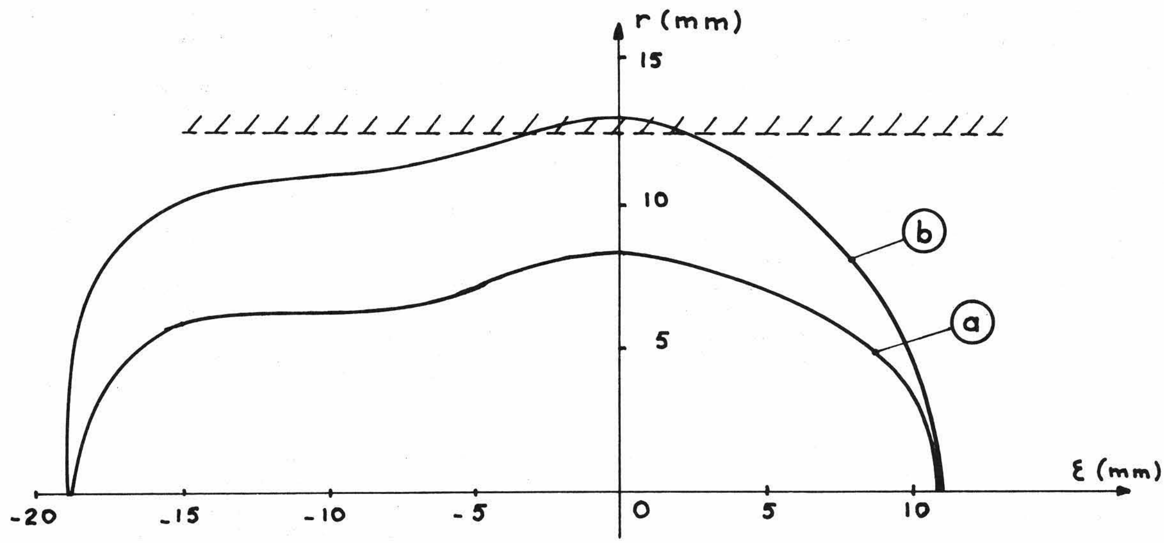

Fig. 8. Acceptance diagram (the dotted line represents the first drift tube aperture): (a) the first gap is focusing; (b) the first gap is defocusing.