A SLOAN-LAWRENCE ACCELERATOR WITH SELF-FOCUSING ACCELERATING STRUCTURE

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Summary

It has been shown in the preceding paper that focusing in a linear accelerator with drift tubes can be achieved if the shape of the extremities of the drift tubes is suitably chosen(1).

We have set out to build a low energy prototype of an ion accelerator in which the results obtained theoritically are exploited . With the focusing system described above,a current gain of about ten times to the unfocused machine was obtained. Without any preliminary bunching device, the output to input current ratio is as high as 10% in good agreement with theory.

Description of the accelerator

The essentially original feature of this model lies in the shape of the drift tubes. The latter are cylindrical, but their ends are prolonged with two diametrically opposed "fingers",whose function is to create a quadrupole field distribution (fig.1). The accelerator is a machine of the Sloan-Lawrence type, employing a symmetrical transmission line. Its basic characteristics are as follows:

Frequency:20 Mc/s
Number of drift tubes:21
Length of the first tube:L=23.08 mm
Length of the final tube:L=80.67 mm
Ratio g/L=0.25 ; Ratio g/h =2
(g and h are defined in fig.1)
Total length of the structure:1.15 mm
Internal diameter of the drift tubes: 2a=10 mm
Diameter of the fingers:10 mm
Diameter of the injection aperture:6mm

The apparatus was designed to accelerate helium He^{+} ions. For this type of ion,the parameters are as follows:

Injection energy:14 keV
Output energy: 200 keV
Maximum gap voltage : 7.7 to 11 kV
Synchronous phase: ϕ_o = 30°

The lengths and positions of the drift tubes are adjustable. They are supported on small stems which can slide along two bars,as the photograph (fig.2) shows.The length of each tube is a function of the RF voltage distribution along the structure.The latter has been measured by means of a new method,which was suggested by the perturbation technique (2).The whole structure is held at the static injection potential (12 to 16 kV), as this simplifies the design of the ion source (which is held at zero potential).

A power oscillator using two pentodes in a symmetrical circuit provides the requisite energy to operate the accelerator. The resonant frequency of the structure is set at 20 Mc/s, by means of a coil which is connected to the bars on the injection side. With this arrangement, the RF voltage increases from the entry to the exit of the accelerator. The oscillator provides RF power of the order of kW; in fact,800 W is adequate to accelerate He^{+} ions up to 200 keV.

The ion source consists of a standard "duoplasmatron",working with helium. The ions are extracted from the discharge plasma by an extraction electrode which is held at the injection potential. A three-electrode einzel lens then enables us to focus the beam onto the entry pupil of the accelerator. Since the diameter of the entry pupil is small (6mm) and the extraction voltages are low,the current injected into the accelerator will be of the order of a few hundred microampères.

Between the injection lens and the accelerator is situated a buncher,which is none other than a single drift tube, placed between a pair of metal planes. As the ions pass through the two successive gaps of this drift tubes,their speed can be varied. The buncher must have as little influence as possible on the radial motion; this will be the case if the RF field is uniform in the two gaps. For this reason,the ends of the buncher electrodes are fitted with grids. The drift tube is excited by means of a RF voltage of the same frequency as the accelerating potential,and of suitable phase . A RF amplifier is coupled to the principal oscillator via a continuously variable delay line,and if it provides a potential of a few hundred volts, the buncher will behave satisfactorily.

The beam detection equipment is placed at the exit of the accelerator. It consists of a mobile Faraday cage, with which the output current can be measured and the shape and phase of the bunches of ions which emerge from the machine can be observed on an oscillograph. (The pass band of the Faraday cage is very wide, about 200 Mc/s. Alternatively, the appearance of the beam energy spectrum can be studied with an energy analyser. The latter consists of an electrostatic deflector with deflection angle equal to 60°, the electrodes of which are supplied with a 50 cycle alternating voltage. The form of the energy spectrum from 0 to 500 keV can then be observed directly on an oscillograph screen.

Calculation of the trajectories-Acceptance

To calculate the trajectories, we use the method outlined earlier[1]. To represent the potential over the cylinder $r=a$, we have chosen the function shown in fig.2 (see ref.1). This model, which seems to be justifiable when the fingers are long in comparison with the gap width might seem to be inaccurate when this is not the case. Nevertheless, we have shown experimentally in an electrolytic tank that for $g=2h$, the value selected in the accelerator design, the model is still satisfactory. By analogy with electrostatic quadrupole lenses, the diameter of the fingers is equal to the interior diameter of the tubes. By selecting this value, only the $n=0$ and $n=2$ (quadrupole) components need be retained in the expansions.

The earlier formulae giving the radial and axial impulses can then be applied directly. We have calculated a large number of trajectories with the aid of an electronic computer (CAB 500). The trajectories within the machine are determined by the four injection parameters, r, $\dot{r}$, ε and $\dot{\varepsilon}$ (the notation is the same as that used in (1). The trajectories are stable (or at least, useful, in the sense that the particles are not lost either through impact against the drift tubes or because they get out of step with the accelerating wave) if the point representing the initial conditions lies within a hypervolume in four dimensions with coordinates $r, \dot{r}, \varepsilon$ and $\dot{\varepsilon}$. Certain sections through this hypervolume are of especial interest, and in particular, the r, ε diagram which is obtained from the intersection with the plane $\dot{r}=0$, $\dot{\varepsilon}=0$. In fact the orders of magnitude of $\dot{r}$ (injected beam not parallel) and of $\dot{\varepsilon}$ (fluctuations of the injection potential) are such that the influence of $\dot{r}$ and $\dot{\varepsilon}$ is considerably smaller than that of r or ε. A number of trajectories which have been traced for common values of $\dot{r}$ and $\dot{\varepsilon}$ have confirmed this approximation.

We have determined the trajectories through the accelerator for a large number of initial values of $r=r_0$, $\varepsilon = \varepsilon_0$ with $\dot{r}=0$ and $\dot{\varepsilon}=0$; we have thus been able to establish the stability zone in the r, ε plane (which is equivalent to the $r, \Delta\emptyset$ plane), shown in fig.3. This diagram displays the influence of the coupling between the r and ε motions very clearly indeed, since the stability region is highly asymmetrical about the $\varepsilon=0$ axis. A similar diagram (the dotted curve) is obtained for the other quadrupole symmetry plane. The acceptance of the machine is different in the two planes, since the first quadrupole is focusing in one and defocusing in the other. The adaptation device suggested by TENG[3], which consisted of a half-lens placed at the entry to the accelerator, seems able to equalize the acceptances in the two symmetry planes.

The results obtained

The purpose of self-focusing structures is to increase the current in drift-tubes accelerators. We have therefore endeavoured to measure the current yield of the machine described above.

The injected current I_1, is the sum of the useful current I_2 collected at the target and the current lost to the drift tubes. The RF potential applied to the tubes allows us to trap the secondary electrons efficiently, and the current lost can be measured without difficultly. The Faraday cage is suitably polarized so that the effect of the secondary electrons is eliminated. The magnitude of the ion energy can be examined simultaneously with the energy spectrograph.

The current yield can easily reach 10% (I_1=200μA I_2= μ20 A) without introducing any device to provide preliminary bunching. As a standard of comparison, we have measured the current yield of the original Sloan-Lawrence accelerating structure.(cylindrical drift tubes with planes ends). In these conditions, the maximum yield is of the order of 1%. This result demonstrates how effective is the focusing system described above. The order of magnitude of the yield can be theoretically obtained by examining the preceding r, ε diagrams. The major limitation on the yield is due to the phase acceptance (of the order of 60°), while the radial oscillations result in a slight loss of particles. The agreement between the yield thus obtained and the experimental results is satisfactory.

The output current, I_2 depends strongly upon the value of the synchronous phase, ϕ_o, and hence, upon the RF power. In fact, when ϕ_o has a value close to zero, the quadrupole effect is very noticeable, but the axial bunching of the ions is poor. For high values of ϕ_o, the reverse is the case, and we therefore expect there will be an optimum value of the synchronous phase. This is indeed what is observed, as the curve plotted in fig.4 shows. The synchronous phase is determined either by measuring the RF voltage on the drift tubes or by determining the phase of the bunches of ions which emerge from the accelerator. The optimum phase is in the neighbourhood of 30°.

With our intruments, we were able to measure the width of the energy spectrum easily, and this is an important characteristic of a linear accelerator. The photograph (fig.5) shows the appearance of a typical spectrum when the complete emergent beam is analysed. The mean energy is 200 keV ±10 keV (the calibration accuracy of the spectrograph) and the half-width of the line is 4,5 keV, or 2,1%. It should be noticed that the shape of the spectrum is not the same for all points over the same cross-section of the beam. This experimental result also reflects the considerable effect due to coupling between the component motions.

We have observed that the output current is limited principally by the phase acceptance, which justifies the use of a buncher. For given accelerator operating conditions (HF potential, injection potential), we find that optimum values of the voltage and phase at the buncher electrode exist (corresponding to adjustement of the bunching parameter and the input phase respectively).

Under these conditions, the current yield can reach 28%. The influence of the buncher on the shape of the energy spectrum is negligible.

Conclusion

We have demonstrated experimentally that quadrupole self-focusing devices, the arrangement with "fingers" in particular, can be used to good effect in drift tube accelerators. The performance of this new type of accelerator is clearly superior to that of a grid machine, for which the yield is never most than a few percent, when heavy ions are being accelerated.

References

(1) BOUSSARD D. Particle Accelerator Conference Washington March 1965, FF18

(2) BOUSSARD D. C.R.Acad.Sci.Paris t 258 p 5375-5378 (juin 1964)

(3) TENG L.C. Rev.Sci.Inst.(1954) 25-3 p 264-268

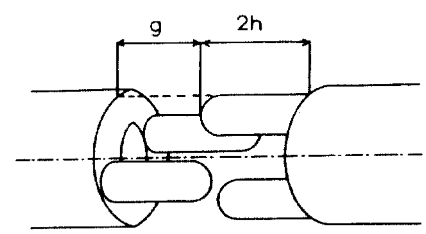

Fig. 1. Drift tubes with "fingers."

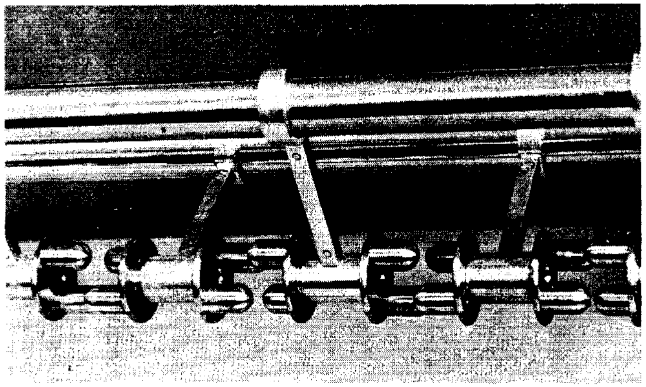

Fig. 2. Photograph of the accelerating structure showing the shape of drift tubes, stems and supporting bars.

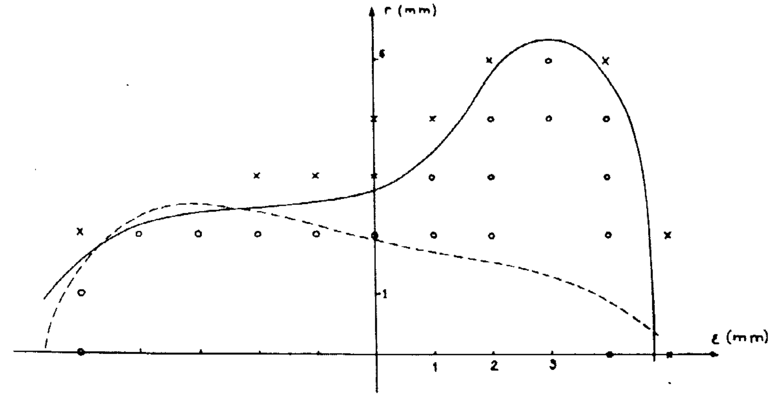

Fig. 3. Acceptance diagram in the r, ε plane. Circles represent stable trajectories, and crossess unstable ones. The diagram is symmetrical about the r=0 axis. The dotted curve is obtained for the other quadrupole symmetry plane.

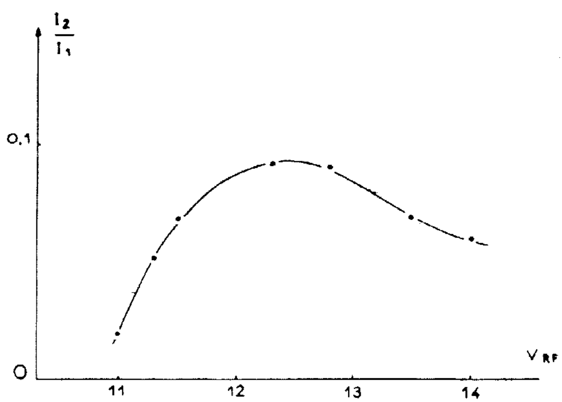

Fig. 4. Current yield vs RF voltage (arbitrary units) without bunching (injection voltage 13 kV).

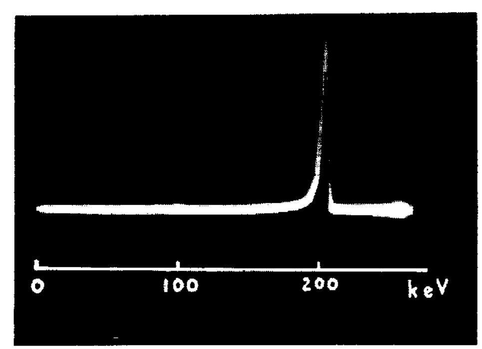

Fig. 5. Typical energy spectrum of the accelerator.