The drift tube design (Fig. 2) allows their alignment onto the axis of the cavity to within 0.2 mm. Adjustment was carried out with an optical method by means of a level and special marks which were placed in each tuning drift tube.

In the accelerating system, beam focusing was carried out by means of grids.

The cavity is placed in a vacuum tank pumped out by two oil-diffusion pumps, with a pumping speed of 4×10^4 l/s. The operating pressure in the accelerator is 1×10^{-6} mm of Hg. The cavity is mounted in the tank on jacks which enable its axis to be brought in line with the tank axis.

A power of 2.5 MW is necessary for acceleration. It is supplied by a push-pull oscillator circuit with tubes —481. The modulation impulse duration is 400 μs.

On the accelerator output, a magnetic analyzer is installed. After the analyzer, the beam is sent to the experimental halls. Tetra-charged carbon ions, tetra-charged nitrogen ions, penta-charged oxygen ions etc. can be obtained with an energy of 10 MeV per nucleon. The current of accelerated carbon ions is 4×10^{-7} A in the pulse. Experimental work with the aim of increasing the output current is in progress.

STRONG FOCUSING IN LINEAR ACCELERATORS

L. I. Bolotin, E. I. Revutskij and V. A. Suprunenko

Physical Technical Institute, UkSSR Academy of Sciences, Kharkhov

In this work the problem of applying " strong " focusing to the proton linear accelerators is considered. A detailed quantitative analysis of proton motion in the system is given. Methods of engineering calculation and the design of quadrupole lenses are elaborated. Experimental results of applying strong focusing in a 5.5 MeV proton linear accelerator are given.

Radial and phase stability cannot be obtained simultaneously in linear accelerators of protons and heavy ions without additional focusing devices. The following methods are used at present for beam focusing in the linear accelerators :

a) focusing grids;

b) longitudinal magnetic field;

c) either electrostatic or magnetic quadrupole lenses.

Grid focusing is extremely simple and reliable in operation, and its use in short accelerators for comparatively small currents is quite justified. But the low " transparency " of this focusing system excludes its use in high energy accelerators.

It is rather difficult to use a longitudinal magnetic field for beam focusing in the beginning of the acceleration because a considerable power supply is necessary. Therefore the most promising method of beam focusing is the use of quadrupole lenses with a variable gradient of the focusing field.

STRONG BEAM FOCUSING IN LINEAR ACCELERATORS

The method of strong focusing was first suggested by Courant, Livingston and Snyder [1] in 1952. The essence of this method is that if we arrange focusing and defocusing lenses of special design in consecutive order, the resulting effect will be a focusing one. Blewett [2] suggested the use of this method for beam focusing in linear accelerators and gave the basic circuit of the quadrupole lens. In this case the fields required for focusing are considerably lower than, for instance, in case of focusing by a longitudinal magnetic field, but they are still rather large. Therefore the attempt undertaken by the Alvarez group [3],

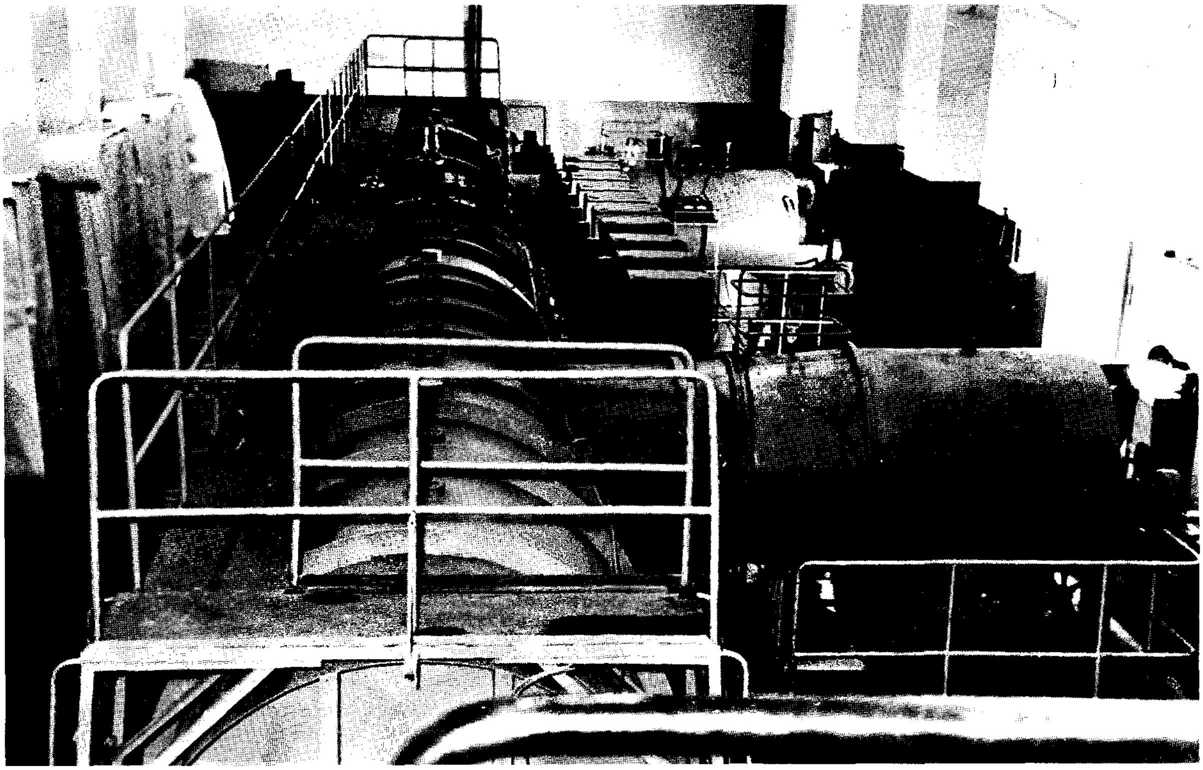

Fig. 1 Multi-charged ion accelerator.

to use this method in a proton linear accelerator for 31 MeV did not lead to a positive result. In 1953 Zelmanov suggested the insertion of a half-length lens at the beginning of the focusing system, which deformed the input beam, deformation being due to the asymmetry of the initial beam parameters in the capture region for strong focusing. Application of this half-lens, and the multiple periodicity suggested by Ya. B. Fajnberg, A. I. Akhiezer, and K. N. Stepanov [4], resulted in a considerable decrease of the field gradient necessary for focusing, and made the present work possible.

When focused by quadrupole lenses during the acceleration process, the particle is acted upon by focusing and defocusing forces in turn. In this case the oscillations of the particle near the axis of the accelerating system can be written as

$$\frac{d^2x}{d\xi^2}+\Omega^2(\xi)x = \varepsilon f(x,\xi) \tag{1}$$

where $\Omega^2(\xi)$ is a quasi-periodic function with alternating sign; ε is a small parameter; $f = \frac{z}{\beta\lambda}$ is a dimensionless longitudinal co-ordinate.

Shershanov in his work [5] gives an approximate solution after one period of the function $\Omega(\xi)$ for the case of $\varepsilon = 0$. The approximate solution is built up from particular solutions at the end of the period which satisfy the initial conditions of the type

$$\begin{aligned} u_{10}(0) &= 1 \quad u_{01}(0) = 0 \\ u'_{10}(0) &= 0 \quad u'_{01}(0) = 1 \end{aligned} \tag{2}$$

Solutions of Equation (1) may be either growing (unstable), or periodic and finite (stable), depending on the character of $\Omega(\xi)$.

Stable solutions are determined by the condition:

$$|\tfrac{1}{2}(u_{10}+u'_{01})| \leq 1 \tag{3}$$

In the case of a symmetric period of the function $\Omega(\xi)$ in the initially defocusing plane (ID), the amplitude of the periodical solution of the Equation (1) may be written [5] in the form of

$$x_m = \sqrt{x_0^2+\left(\frac{x'_0\beta\lambda}{\Gamma}\right)^2}\sqrt{\frac{\Gamma(0)}{\Gamma(\xi)}} \tag{4}$$

where the parameter Γ is the ratio of matrix elements calculated for the initial defocusing plane,

$$\Gamma^2 = -\frac{u'_{10}}{u_{01}}$$

and X_0 and X'_0 are the initial deviations in cm and the initial angle of the particle trajectory in radians, respectively.

For the initially focusing plane, we have an analogous expression for the amplitude, only the value Γ is expressed by the matrix elements calculated for an *initial* focusing plane.

The second co-factor in Eq. (4) takes into account the change of the amplitude during the acceleration.

In some cases it is more convenient to use the expression suggested in other works [6,7], which can be written to a sufficient approximation in the form

$$x_{HD} = \sqrt{(\gamma x_0)^2+\left(\frac{x_0^1\beta\lambda}{\gamma\Gamma}\right)^2}\sqrt{\frac{\Gamma(0)}{\Gamma(\xi)}}$$

where Γ is calculated for the initial focusing plane, and

$$\gamma^2 = \frac{\Gamma_{H\phi}}{\Gamma_{HD}}$$

It is easy to show that for the initially focusing plane the amplitude may be written down in an analogous way if $\gamma = 1$.

CALCULATIONS OF PARTICLE MOTION IN A STRONG FOCUSING SYSTEM AND CHOICE OF THE OPERATING POINT

In a number of published articles [6,7], diagrams for stability regions were given with values of the parameters γ and $\Gamma_{H\phi}$ plotted on them. However the formulae according to which calculations were made contained rather rough approximations, which

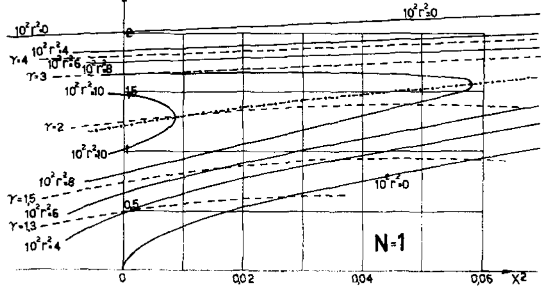

Fig. 1 Region of stability for $N = 1$.

rendered the diagrams almost useless. The authors therefore considered it necessary to recalculate more precisely the stability regions, so that they might be more useful for real design work.

Figs. 1, 2, 3 show the regions of stable solutions of Eq. (1) for different combinations of focusing and defocusing lenses and numerical values of $\Gamma_{H\phi}$ and γ respectively, calculated according to the papers of Shershanov[5] and Vlasov[7], in the case when the function $\Omega(\xi)$ has the form

$$\Omega(\xi) = \begin{cases} i\dfrac{1}{1-\alpha}Y & \text{in defocusing lens} \\ i\alpha X & \text{in accelerating gap} \\ \dfrac{1}{1-\alpha}Y & \text{in focusing lens} \end{cases} \qquad (5)$$

Here

$$X^2 = \frac{z\alpha\pi eEG\lambda}{Amc^2\beta}\cdot\sin\phi_s \qquad (6)$$

$$Y^2 = \frac{z(1-\alpha)^2 eV\kappa\lambda^2}{Amc^2a^2} \qquad (7)$$

for the case of electrostatic lenses,

$$Y^2 = \frac{300z(1-\alpha)^2 eH'\beta\lambda^2}{Amc^2} \qquad (7a)$$

for the case of magnetic lenses.

H′ —the magnetic field gradient,
V —potential difference on lens electrodes,
K —factor depending on the electrode shape,
λ —wavelength,
$2a$ —lens aperture,
α —ratio of the gap length to the length of the period.

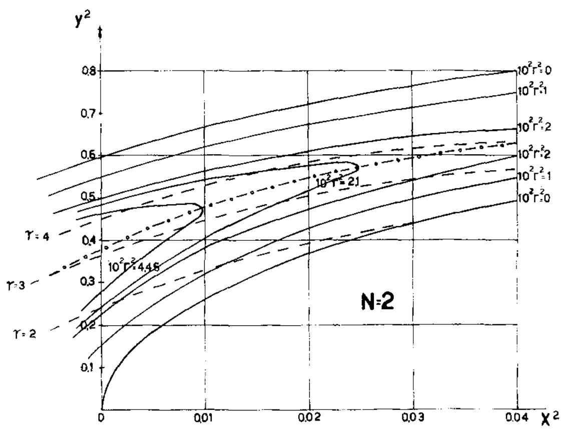

Fig. 2 Region of stability for $N = 2$.

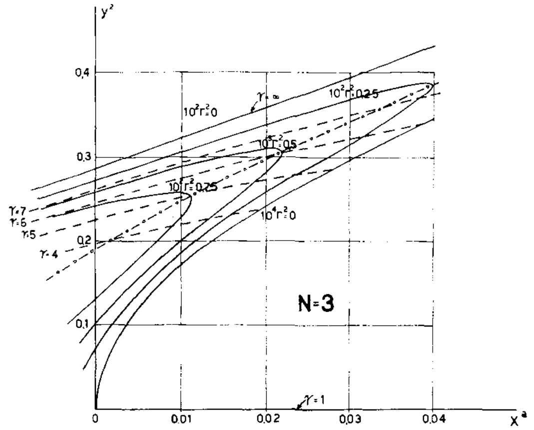

Fig. 3 Region of stability for $N = 3$.

In all calculations it is assumed that $\alpha = 0.25$; $\beta = v/c$ is the initial relative velocity of the ion; Z and A are the numbers of charge and mass respectively; ϕ_s is the synchronous phase; E is the amplitude of the accelerating field averaged over the accelerator length. G is a factor of accelerating field use, for $\alpha = 0.25$ maximum value of $G = 0.9$.

Focusing systems for which stability areas are plotted in Figs. 1, 2, 3 differ from each other by the number of successively located lenses of the same sign (of multiple periodicity). These diagrams show that if one chooses an operating point in the middle of a stability area, the lens voltage necessary for focusing will decrease (as $2^{-(N-1)}$) with increasing number N of successively located lenses.

However it is seen from the diagram of motion in the phase plane (Fig. 4), that with increasing N the oscillation amplitude in the defocusing plane grows considerably depending on the beam radius, and the capture region becomes narrower. It should be noted that the dependence of the ion oscillation amplitude on the input beam parameters is determined by the first lens sign. For an initial focusing plane, the amplitude has a sharp dependence upon the beam angular divergence, and for an initially defocusing plane the amplitude depends but little upon angular divergence, but it grows rapidly with the increase of input beam diameter. In Fig. 5 we can see the capture regions on phase plane depending on lens voltage, when $N = 2$. It is seen that the largest capture is observed for a paraxial

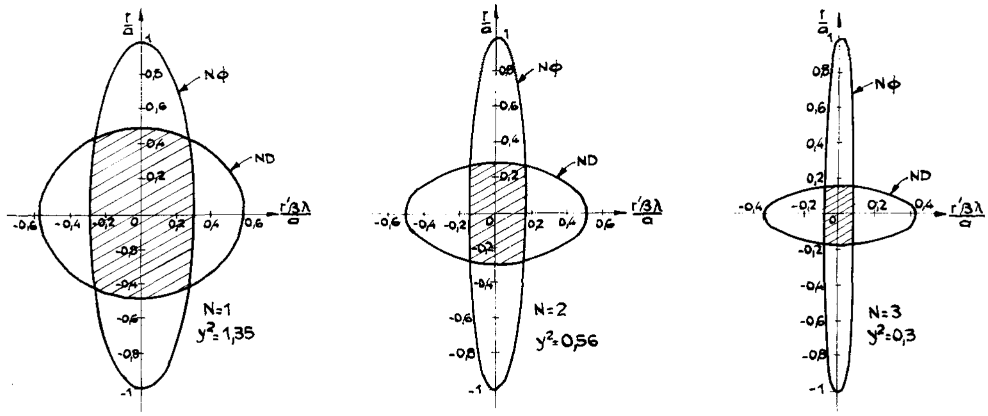

Fig. 4 Regions of capture by input beam parameters for different N, when $X^2 = 0.02$.

beam. In this case the operating point is near the lower boundary of the stability region. When the lens voltage increases, the capture region decreases abruptly because of the increase of oscillation amplitude in the initially defocusing plane (γ rises abruptly). Fig. 6 shows proton paths in the 5.5 MeV linear accelerator. The upper envelope of these paths is described by a periodic solution of the Eq. (1). The period is determined by the expression $T_{pag} = \frac{2\pi}{\Gamma}$, where Γ is the mean value of $\Gamma(\xi)$ by acceleration interval.

In the case when the phase-oscillation period becomes an integral multiple of the radial oscillation half-period, a parametric resonance will take place. $T_{\phi az} = m\frac{T_{paq}}{2}$ where m is a whole number, and

$$T_{\phi az} = \frac{\pi}{X\sqrt{2}}.$$

It is always possible to choose the lens voltage in such a way that either the resonance conditions are not satisfied at all, or are satisfied during only a small part of the acceleration, which is considerably smaller than the period of radial oscillations. In this case resonance will not apparently lead to an appreciable amplitude increase.

As it is seen from Fig. 6, the amplitude of radial oscillations will increase with the acceleration of the ion relative velocity at the expense of the cofactor

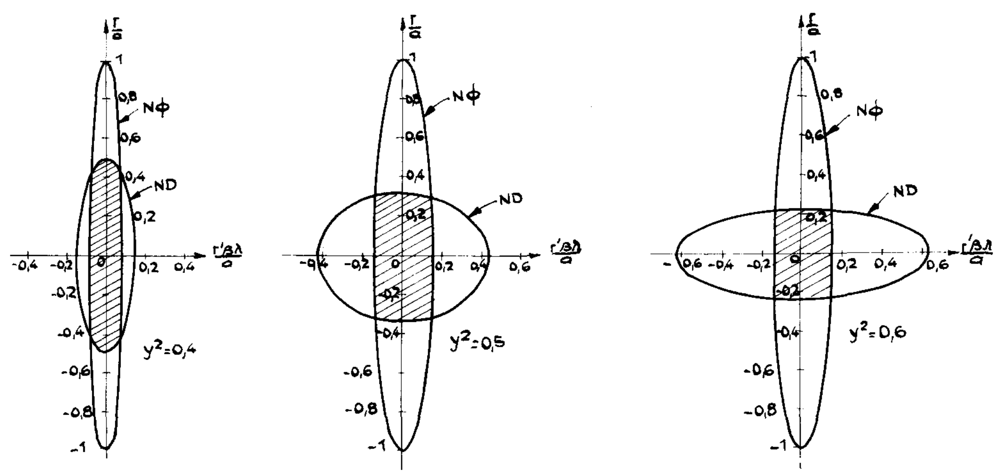

Fig. 5 Regions of capture by input beam parameters for lens different voltage, when $N = 2$ and $X^2 = 0.02$.

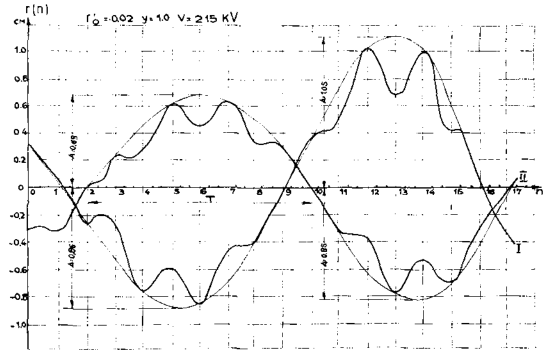

Fig. 6 Ion path in (IF) and (ID) planes in linear accelerator under initial conditions $X_0 = 0.02$ radian and $X_0 = 0.3$ cm, $N = 1$ and voltage $v = 22$ kv. (I. First lens focusing; II. First lens defocusing).

in Eq. (4) $\sqrt{\frac{\Gamma(0)}{\Gamma(\xi)}}$. This is accounted for by a decrease of $\Gamma(\xi)$ with increase of ion velocity if the gradient of the lenses is constant along the system.

Calculations were carried out for the ratio of the amplitude at the beginning to that at the end of the acceleration, as a function of the lens voltage. It is shown that the least amplitude increase will take place when the voltage is near to the stability region lower boundary. If the lens voltage is changed as the ion accelerated velocity is increased so that $\Gamma(\xi)$ remains constant, the amplitude will not increase.

As the focusing effect in the system investigated is differential, the so-called " strong " focusing, as a matter of fact, is rather weak ($\Gamma \ll 1$). Therefore this system makes great demands of accuracy on the assembling and lens manufacturing, and also on the allowable pressure fluctuations on them.

The mean square amplitude increase of radial oscillations caused by an inaccuracy in assembly may approximately be expressed by the relations (6) and (8):

$$\delta x = \frac{Y^2\sqrt{n}}{\sqrt{3(1-\alpha)}\Gamma}\sqrt{\left(1+\frac{1}{\gamma^2}\right)\frac{\Delta^2}{4}+\frac{3}{2}\frac{x_{H\Phi}^2}{\gamma^2}\chi^2+\left(1+\frac{1}{\gamma^4}\right)\frac{x_{HD}^2}{16}\rho} \qquad (8)$$

where $\Delta = \frac{\Delta X_{in}+\Delta X_{fin}}{2}$ is the tolerance on shifts of a lens centre from the axis and

χ is the tolerance on deviations of lens axes from the accelerator axis;

ρ is the tolerance on the lens proper parameters:

$$\rho = \frac{\Delta V}{V}+2\frac{\Delta a}{a}+2\frac{\Delta l_{\text{lens}}}{l_{\text{lens}}}$$

n is the number of drift tubes with lenses.

This formula is deduced supposing that the effect of the lens is equivalent to a radial impulse in the drift-tube centre. In this case the calculations become considerably simpler but important singularities of motion are not missed. Errors within the tolerances are assumed to be distributed with equal probability.

The main influence on the amplitude is thus exerted by shifts of the zero-field axis, the non-orthogonal intersection of lateral axes, and by fluctuations of lens field-intensity around the specified value.

To decrease current losses with given tolerances it is necessary either to increase the lens aperture or to improve the beam focusing at the system input. Since lens voltage increases as the square of the aperture, it is expedient to concentrate on improving the injected beam parameters.

Considering the practical problem of tolerances for lens manufacture and assembly, and the problem of obtaining the necessary lens gradient, it is expedient to study the influence of the electrode form on field topography. Taking into account the symmetry in the electrode distribution, the field in a quadrupole lens can be written in the form:

$$\frac{V(x)}{V_0} = -K_1\frac{x^2}{a^2}-K_2\frac{x^6}{a^6} \qquad (9)$$

where K_1 and K_2 are factors depending on the electrode shape. Bernard [9] calculated the value of the factors K_1 and K_2 for some forms of electrodes shapes and showed that the greatest field gradient is obtained with cylindrical electrodes.

For the case of hyperbolic electrodes, the dependence of the gradient on h/a was determined by the authors using an electrolytic model. Due to this dependence, it is possible to determine the most advantageous way of representing hyperbolic branches. It is shown that, with great accuracy, the hyperbola may be replaced by a circular arc with radius $R = 1.1\,a$.

CALCULATION OF THE FOCUSING SYSTEM FOR A LINEAR ACCELERATOR

For a focusing system calculation it is necessary first to choose the number of lenses with one sign (N) situated in successive drift tubes.

From the stability diagrams of Figs. 1, 2 and 3, with predetermined values of X^2 we obtain the magnitude of the parameter Y^2, the value of which determines the necessary focusing voltage, the aperture being fixed.

Investigations of strong focusing were carried out on a proton linear-accelerator with energy 5.5 MeV. Its parameters are $\lambda = 2.18$ m, $E = 20$ kV/cm, $\beta_0 = 0.0328$, $\beta_{fin} = 0.1$, $\phi_s = 16°$, $k = 1$, $G_0 = 0.5$, $X_0 = 0.141$. We chose aperture $2a = 1.5$ cm and $N = 2$. From the stability diagrams we chose $Y^2 = 0.4$, so that $\gamma = 2$, and $\Gamma(0) = 10^{-1}$.

With these values the necessary voltage on the lens electrodes was 8 kV. The parameters of the ellipses in the phase-plane (see Fig. 5) are the following:

For ID plane :

$$\frac{X_m}{a} = \frac{1}{\gamma} = 0.5\,; \quad \frac{X'_m}{a} = \frac{\gamma\Gamma}{\beta\lambda} = 2.8 \times 10^{-2}\ .$$

For IF plane :

$$\frac{X_m}{a} = 1\,; \quad \frac{X'_m}{a} = \frac{\Gamma}{\beta\lambda} = 1.4 \times 10^{-2}$$

where X is angular divergence of the input beam.

In our case, the input beam diameter in the linear accelerator had to be less than 0.75 cm, and the angular divergence less than 2.1×10^{-2} radians in divergence.

Taking into account inaccuracy of manufacture these dimensions must be further reduced.

Let us take, for example, the following system of tolerances :

1. The shifting of the lens-ends from the accelerator axis ΔX initial and ΔX final : 0.01 cm.
2. The inaccuracy of location of axes $0X$ and $0Y$:
$$\chi = 0.02 \text{ rad} = 1.5^0\ .$$
3. The spread of the parameters of the lenses is
$$\rho = \frac{2\Delta V}{V} = 0.05\ .$$

Taking into account the number of drift tubes $n = 20$, from Eq. (8) we get a root-mean-square increase of amplitude $\delta X = 0.32$ cm.

Consequently, with this system of tolerances, the effective lens aperture decreases approximately by 3 mm, i.e. $2a$ eff $= 1.2$ cm.

Hence we can determine the parameters of the input beam which may be transmitted through the accelerator without losses which are $2X_0 = 0.6$ cm $2X'_0 \simeq 1 \times 10^{-2} \simeq 0.5^0$.

One should not forget that with an increase of lens aperture, the influence of inaccuracy of the axes $0X$ and $0Y$ and the spread of proper lens parameters grows considerably compared with shifts of lens-ends.

LENS DESIGN

It is possible to create fields with variable gradients by means of electrostatic or magnetic quadrupoles. To apply electrostatic quadrupoles it is necessary to place electrodes with a potential of 40~50 kV in a small volume of drift tube.

Two designs of quadrupole lenses were considered. One of them has an aperture $2a = 1.5$ cm for a voltage of 15 kV, the other had an aperture $2a = 3.0$ cm with a voltage of 40 kV. In the latter case it is difficult to make an insulator of small overall dimensions for high voltage operated in vacuum. Great difficulties were caused by the high-voltage supply

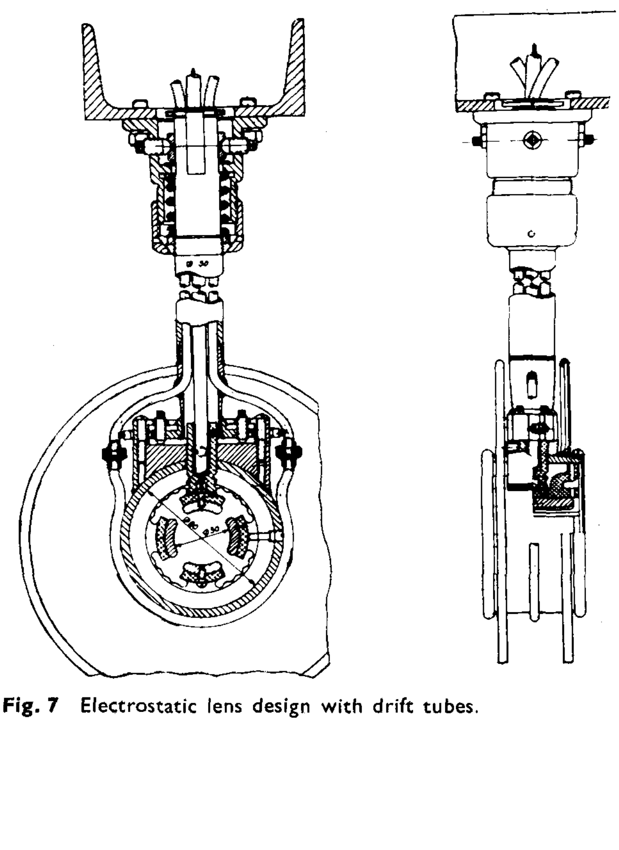

Fig. 7 Electrostatic lens design with drift tubes.

to the lens electrodes due to discharges over the feeding cable surface The design of a drift tube with a lens for the 5.5 MeV accelerator with an aperture $2a = 3$ cm is shown in Fig. 7.

The lens electrodes, made of duralumin, were fastened to the body of organic glass. A feed-through insulator was installed to eliminate ruptures over the cable surface.

Special measures were taken to prevent the penetration of the high-frequency accelerating field into the inner portion of the drift tubes with lenses. Their presence would reduce the electric field strength of the vacuum gap between the electrodes. In the case of electrostatic lenses, investigations were carried out with two forms of electrodes: hyperbolic $k = 1$; $2a = 1.5$ cm and cylindrical $k = 1.275$; $2a = 3$ cm. This paper contains experimental results for the hyperbolic electrodes. Somewhat different results were obtained for lenses with cylindrical electrode shapes; they need further interpretation and will be published later. Only electrodes of cylindrical shape were used for electromagnetic lenses.

LENS MOUNTING IN THE ACCELERATOR

Three problems encountered were:

a) the problem of lens-axis position alignment;

b) the problem of the alignment control of the lens and accelerator axes together;

c) the preservation of the alignment within time.

To regulate the position of the lens axis, a design shown in Fig. 7 was developed. It consists of two adjustment units, an upper and a lower one.

By means of four micrometer screws and a coupling nut, the upper unit allows the alignment of the centre of the drift tube with the accelerator axis.

The lower unit consists of a ball-joint with micrometer screws; it allows the lens and accelerator axes to be brought in line. Control of lens-axis position is carried out by means of an HA−1 precise level and of marks which were located in the gap between the electrodes.

The design of the marks is shown in Fig. 9. The distance between dashes was calculated as a function of the distance between the level and the controlled lens. This methods allowed the lens adjustment to be controlled with an accuracy of ± 0.1 mm. The

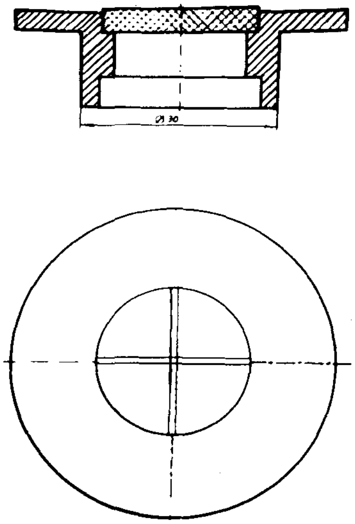

Fig. 9 Mark drawing for drift tube adjustment.

gap adjustment between drift tubes was carried out by means of a mechanical indicator.

An important condition for the normal accelerator operation is that during tuning and operation the exact arrangement of drift tubes should be maintained. The design of the drift tubes and the endovibrator fastening ensures adjustment rigidity for all the period of accelerator operation.

EXPERIMENTAL INVESTIGATIONS OF THE FOCUSING SYSTEM OF THE 5.5 MeV LINEAR ACCELERATOR

Experiments to verify the focusing system calculations were carried out on the proton 5.5 MeV linear accelerator. By the beginning of 1955 the calculation and design of the system was complete, and by the end of 1955 the first experimental results were obtained. The proton energy was measured at the linear accelerator input and output, the input diaphragm openings and lens voltage being varied.

Current measurements at the accelerator input were carried out by means of a Faraday cylinder placed directly at the accelerating system input.

Output current measurements were also carried out by means of a Faraday cylinder situated at a distance of 2m from the accelerating system. External beam focusing between the accelerator output and the Faraday cylinder was not applied. The dependence of the accelerator output current upon lens voltage is given in Fig. 8. For the case of optimum conditions

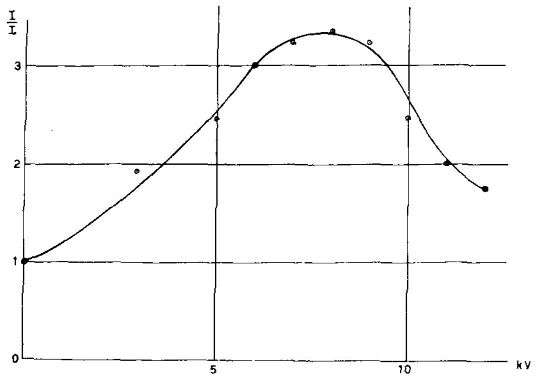

Fig. 8 Current dependence on accelerator output of lens voltage.

of accelerator operation, the maximum current is obtained with a lens voltage of 8 kV (see Fig. 8), which corresponds to the lower boundary of the stability region and agrees with calculation.

This diagram shows that a change of lens voltage by 20% does not lead to a considerable current decrease at the accelerator output.

By varying the lens operating voltage, the accelerator output current could be increased 3-4 times and had a strong dependence on the injected operating conditions, i.e. on input beam divergence. The relatively small current increase by lens switching is due to the small length of the accelerator. When the accelerator output beam was studied with no lenses, the input-output current ratio was 1/30. With a lens the ratio is 1/7 and largely depends on the accelerating field intensity. With a lens diameter of 15 mm, the beam diameter was about 6 mm, which is in good agreement with calculation.

Under the same conditions but with grid focusing, the current ratio was 1/20, but the beam diameter was 30 mm, the grid aperture being 35 mm. This fact shows that the use of strong focusing necessitates a well focused beam at the accelerator input.

Our calculations and experimental investigations show the practical possibility of the use of strong focusing in ion linear-accelerators with drift tubes.

Tolerances on manufacture and alignment are such that the accelerating system may be realized, provided the lens diameters are chosen carefully. Furthermore, the necessary lens voltages for focusing could be considerably decreased by changing to a longer wavelength, since $v \sim 1/\lambda^2$; and also by decreasing the accelerating mean field intensity.

PULSED MAGNETIC LENSES FOR A PROTON LINEAR ACCELERATOR

Thus the investigations showed that the application of electrostatic lenses was useful. In some cases, however, as, for example, in the case of strong currents in the accelerated particle beam, it is desirable to use magnetic quadrupole lenses. Calculations made in this work show that a power input of 250 kW is necessary for feeding the magnetic focusing system with gradients of alternating sign for a proton linear accelerator of 30 MeV with injection at 4 MeV. It is apparent that it is rather a difficult technical task to arrange such lenses together with their cooling system in drift tubes. Since the majority of linear accelerators operate at present under pulsed conditions one should consider the possibility of magnetic quadrupoles fed by pulsed currents. Calculations of the system with gradients of alternating signs (see formula (7a) show that magnetic field-gradient in the lens necessary for focusing is determined by the ratio

$$H' = \frac{Amc^2\beta_0 Y^2}{Ze\cdot 300 l_l}$$

where l_l is the length of the lens.

In the case considered $Y^2 = 0.4$. The magnetic induction in the pole shoe may be approximately determined as $\beta_{ir} \simeq H'a$.

The number of ampere-turns for one pole necessary to create such a gradient, not taking into account the magnetic resistance of the pole faces and the yoke, is determined by:

$$nI \simeq 0.1H'(2a)^2 \ .$$

The lens design is shown in Fig. 10. The body is manufactured of transformer steel, the thickness of the

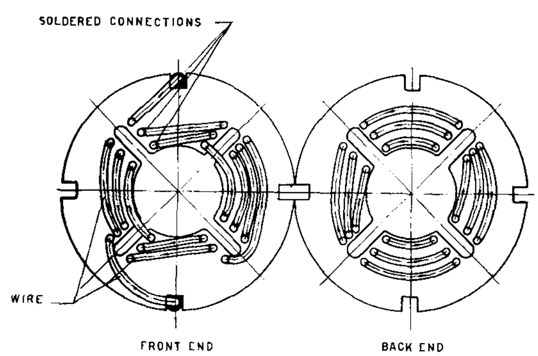

Fig. 10 Winding arrangement in pulsed magnetic lens.

sheets being 0.35 mm. The winding is made of mark ПЭВ—2 wire of 2 mm diameter. The wires were coated by ВФ—2 glue layer, then they were inserted into the pole slots and baked. The resulting winding was rather durable mechanically, capable of withstanding the impacts arising when pulse currents of the order of 2 000 A are passed.

For the proton accelerator up to 5.5 MeV the necessary magnetic field gradient in the first lens is $H' = 1.42 \times 10^3$ Oe. The number of ampere-turns per pole is $nI = 1000$ ats. With three turns, about 300 A is necessary, or about 600 A per lens, the winding connection being series-parallel. The current necessary for parallel feeding of 20 such lenses is about 12000 A.

Such currents were obtained from a step-down transformer with a transformer ratio of 100 : 1 by means of a long-line discharge the capacitance of which is 60μF. The transformer secondary winding consisted of two turns of copper bar with cross-section of 700 mm^2. The bus-bars were of the same cross-section. The lens field-gradient measurements were carried out by means of Hall effect on bismuth. Measurements show that an insignificant winding asymmetry does not result in the disturbance of magnetic field distribution in the lens. Terminal voltage of the lens was about 10 V. Mean power dissipated in the first lens at one pulse per second and a pulse duration of 500 μs is about 15 W. The mean power which is necessary for the whole system is about 250 W.

It was found experimentally that at the first lens, the pulse reaches peak amplitude considerably earlier than in the last one. This rather undesirable effect can be explained by different values of lens inductance. Indeed, the time for growth of the lens current pulse is $\tau = L/R$ where R is lens effective resistance, L is inductance which can be determined from the formula

$$L \simeq 0.8\pi \frac{nKS \cdot 10^{-8}}{\left(a + \frac{l_{ir}}{\mu_{ir}}\right)}$$

where l_{ir} is the mean magnetic line length, S is winding turn area, and n is the number of winding turns.

For the first lens $\tau = 160$ μs, for the 20th it is 500 μs. The current pulse in the last is consequently delayed by 340 μs compared with the first. To eliminate this effect, focusing system should be divided into sections separately fed.

It should be noted that this system demands very firm attachment of the lenses to the drift tubes, because at the moment of the pulse there is a strong transient force. The system shown was investigated in the 5.5 MeV proton linear accelerator. The results were analogous to those obtained with electric lenses. Somewhat larger current losses in this system may be accounted for by insufficiently rigid fastening of the drift tubes.

The laboratory staff is now carrying out further lens design improvement. More detailed results of this work will be published later.

In conclusion the authors consider it their duty to express acknowledgement to Professor K. D. Sinelnikov, member of the Uk.SSR the Academy of Sciences and to Ya. B. Fajnberg for their constant interest in the work and valuable discussion.

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