DESIGN AND DEVELOPMENT OF PERMANENT MAGNET QUADRUPOLES FOR ION LINACS

I.M. Kapchinskij, A.M. Kozodaev, N.V. Lazarev and V.S. Skachkov
Institute for Theoretical and Experimental Physics, Moscow

Strong focusing in all of the operating linacs of Alvarez type is now being accomplished by means of magnetic quadrupole lenses supplied by constant or pulsed current. The use of electromagnetic lenses was caused by two reasons: the first - a requirement of continuous control of the field gradient in each lens, specifically selection of the gradient slope along the axis of the accelerator, and the second - for lack of the suitable hard magnetic materials with required magnetic fluxes.

Up to the present there is accumulated reach experience of operation with strong focusing linacs at relatively high pulsed currents of order 100-200 mA[1]. It turned out individual selection of current in lenses coils is practically impossible because of too large quantity of the degrees of freedom, which are to be selected. That is why the calculated values of currents are set. If one attempts to increase the intensity of the accelerated beam, then sometimes occurs the necessity to control the slope of the gradients along the accelerator axis due to the space charge influence on the frequency of incoherent transverse oscillations. However, the optimum slope of the gradients for acceleration of maximum currents may be calculated beforehand. The value of the slope itself is not critical for acceleration of beams with intensities lower than maximum. So, the long experience of operation of the linear accelerators allows to confirm, that there is no necessity to control the gradients of the quadrupole lenses.

Some constructions of permanent magnet quadrupoles were proposed for focusing of proton beams in ion guides[2,3]. Permanent magnets, which make the fluxes in the effective aperture of the focusing channel, has the required temperature and time stability, are stable to mechanical vibrations and allow to keep the tolerances on the focusing field gradients[4]. Recently it was shown[5], up-to-date hard magnetic materials are able to ensure quite enough acceptance of a linear accelerator focusing channel.

For proton beam acceleration with pulsed current up to 200 mA at injection energy 700-750 keV and phase density 1 A/cm.mrad, it is necessary to get the value of normalized acceptance be about 1 cm.mrad[6]. If the wavelength of the accelerating field is 2 m and energy gain is between 0.9 - 1.25 MeV/m, the normalized acceptance 1 cm.mrad is possible to get with the radius of the aperture 1 cm and maximum gradient of the electromagnetic lens field accordingly 4.5 - 6.0 kGs/cm[7,8]. With the increase of the particles energy the gradient of magnetic field under fixed normalized acceptance of the channel quickly decreases.

The models of permanent magnet quadrupoles were constructed in ITEP for experimental confirmation of the possibility to achieve the fields with gradients up to 6 kGs/cm in lenses with such o.d. to allow to put them into the drift tubes.

The main parameter of magnetic system is the leakage coefficient. The leakage coefficient defines the useful part of the full magnetic flux generated by permanent magnet. It seems useful to define of the leakage coefficient of the quadrupole lens magnetic system as a ratio flux in the neutral section of the pole to the flux through the median plane of the lens within the limits of the effective aperture. The field at the median axis is assumed to be ideal - with constant gradient, equal to the value, $G = \partial By/\partial x$ in the center of the lens. We shall treat the radius of effective aperture a to be equal to the distance between the center of the lens and the pole tip. Then the leakage coefficient is:

$$\sigma = \frac{B_m \ell_H}{G\, a^2}, \tag{1}$$

where B_m - the mean value of the magnetic induction in the neutral section of the pole. Every of the four hard magnetic poles is made as a bar of width ℓ_H and length ℓ_M.

Since relative permeability of a soft magnetic circuit is very high it is possible to neglect the intensity of magnetic field in the magnetic circuit. The mean value of the magnetic field intensity along the axis line of the pole is connected with the gradient in the center of the lens by the equation

$$\mu_o \bar{H}_m = \frac{G\, a^2}{2\ell_M} \tag{2}$$

The operating point on the demagnetization curve must be chosen near the optimum regime ($B_m = B_d$, $H_m = H_d$), corresponding to the maximum density of the magnetic energy in the bar.

Let us suppose that $\bar{H}_m = H_m/\chi$; then the operating point is defined by crossing of the demagnetization curve with the direct line

$$\frac{B_m}{\mu_o H_m} = \frac{2\sigma\, \ell_M}{\chi\, \ell_H} \tag{3}$$

As it was shown by our measurements, in spite of considerably large value of χ , induction in the neutral section remains quite close to optimum owing to that the top of the demagnetization curve of the used materials was rather flat. Therefore it is possible to assume $\chi \simeq 1$ under calculation width ℓ_H and length ℓ_M of the pole through expressions 1 and 2.

Among the wide spread and rather cheap hard magnetic materials the alloys ЮНДК25БА and ЮНДК35Т5БА may be distinguished because of their good parameters: $(BH)_{max} = 8.5 + 12 \cdot 10^6$ Gs·Oe[9]. Let us consider the possible parameters of lenses made of the alloy ЮНДК35Т5БА, for which $B_d = 9$ kGs and $H_d = 1.23$ kGs. The results of our experiments with models of quadrupole lenses with flat pole tips choose to suppress the fifth harmonic of the field, show that $\sigma \simeq 5$. Assuming $\mu_o H_m \simeq 1$ kGs, when the radius of aperture a = 1 cm and gradient G = 6 kGs/cm, it is easy to get, that $\ell_H = 3.5$ cm and $\ell_M = 3$ cm. Such lens may be easily placed inside the 15 cm o.d. drift tube. For comparison, o.d. of the first drift tubes in the linacs of LAMPF, BNL, NAL and SACLAY are 18 cm[10]. The decrease of magnetic field gradient in the drift tubes along the accelerator axis is more rapid than the increase of the square value of aperture radius. Then the dimensions of the permanent magnets at the following quadrupoles decrease.

The approximate calculations show that it is possible to construct the permanent magnet quadrupoles for strong focusing of proton beams in drift tube linacs through the whole energy range, beginning from the injection energy.

The photo of the model of the quadrupole lens for a drift tube with the alloy ЮНДК35Т5БА poles made in the form of the rods is shown in Fig. 1. The pole tips and the yoke closing the magnetic flux are made of the soft steel. The o.d. of this lens is 11.8 cm and aperture - 2 cm. The gradient reached G = 3.67 kGs/cm, that corresponds $\sigma = 4.7$. There are all reasons to believe that under corresponding increase of the o.d. of the lens for the first drift tubes, it is possible to reach the value of the gradient up to 6 kGs/cm.

Recently there was shown an interest[11] to focusing channel on permanent magnets of a linac for medical purposes.

The use of permanent magnet quadrupoles allows to get rid of rather cumbersome system of stabilized current power supplies for electromagnetic lenses in the drift tubes. The problem of cooling becomes much simpler, especially compared with cases when strong focusing is carrying out by electromagnetic lenses, the coils of which are fed by d.c. As there is no coils, the ratio of the length of the quadrupole to the length of the drift tube may be increased. It allows to decrease the necessary values of field gradients under fixed transverse oscillations frequency. It becomes easier to place two quadrupoles in one drift tube. Use of melted permanent magnets will allow, perhaps, to refuse of the requirement to have hermetic drift tubes. The manufacturing of the drift tubes will be much simpler.

DISCUSSION

P.V. Livdahl, FNAL: Have you experienced variations in quadrupole field strength and quality?

Lazarev: No production has been made as yet.

Livdahl: Have you made any quadrupoles of larger bore?

Lazarev: Not yet. At first we want to make the most difficult quadrupole for the first drift tube.

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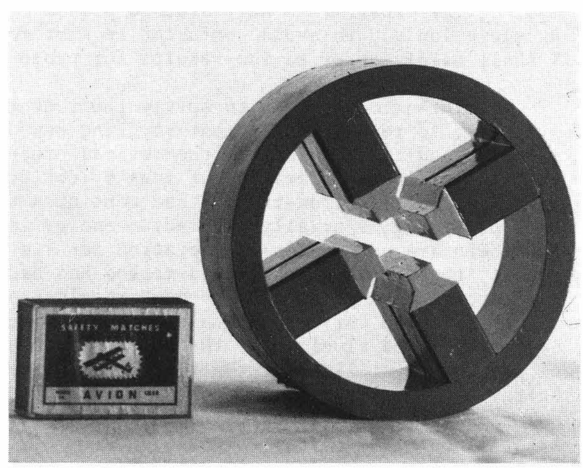

Fig. 1 Model of the quadrupole lens for a drift tube linac.