MAGNETIC FIELD OF THE 700 MEV RELATIVISTIC PROTON CYCLOTRON

By

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This paper deals with the calculation and model studies of the magnetic system of the 700 Mev relativistic proton cyclotron [1]. The magnetic field in the median plane of the accelerator must be formed with an accuracy of $\pm 1 \times 10^{-2}$ for variations on extreme radii and of $\pm 3 \times 10^{-4}$ for the average field value [2]. The determination of the parameters of the magnetic system which safeguard the given tolerances has been carried out in three stages: At first a theoretical calculation of the magnetic field of different elements of the magnetic system was made, then the single elements of the magnetic system were designed and finally the entire magnetic system of the accelerator developed.

The magnetic field of the spiral shims which form the variation has been calculated under the assumption of a uniform magnetization of shims along the external magnetizable field. In this case the magnetostatic potential of two rectilinear shims located symmetrically with respect to the plane z = 0 and limited along the vertical by the surfaces $z = h_1(r)$ and $z = h_2(r)$ for the region $|z| < h$ is determined by the expression

$$\Phi(r, \varphi, z) = 2\sum_{m=0}^{\infty} \varepsilon_m \int_s M(r') \cos m(\varphi - \varphi') \int_0^{\infty} [e^{-\lambda h_1(r')} - e^{-\lambda h_2(r')}] \operatorname{sh} \lambda z J_m(\lambda r) J_m(\lambda r') \, d\lambda \, ds, \tag{1}$$

where $\epsilon_m = 1$ at $m = 0$; $\epsilon_m = 2$ at $m > 0$; J_m is the Bessel's function and M(r) the intensity of magnetization of shims along the axis z [3]. If the area of integration s is limited by the arcs of the circumference $r = R_H$ and $r = R_K$ and by curves of the shape of an Archimedian spiral $r = N\lambda(\varphi - \frac{\alpha}{2})$ and $r = N\lambda(\varphi + \frac{\alpha}{2})$, then the average magnetic field, the amplitudes and phases of the harmonics of the system of N pairs of spiral shims shifted against each other by the angle $\theta = \frac{2\pi}{N}$ $(\theta > \alpha)$, are determined by the corelations

$$H(r) = NH(r, h_1) - NH(r, h_2), \tag{2}$$

$$H_k(r) = N\sqrt{[H_k^s(r, h_1) - H_k^s(r, h_2)]^2 + [H_k^c(r, h_1) - H_k^c(r, h_2)]^2}, \tag{3}$$

$$\beta_k(r) = \operatorname{arctg} \frac{H_k^s(r, h_1) - H_k^s(r, h_2)}{H_k^c(r, h_1) - H_k^c(r, h_2)}, \tag{4}$$

where

$$H(r, h) = \frac{2\alpha}{\pi r \sqrt{r}} \int_{R_H}^{R_K} M(r')[-Q'_{-1/2}(x)] \frac{h(r')}{\sqrt{r'}} dr';$$

$$H_k^{s,c}(r, h) = \frac{8M \sin k\frac{\alpha}{2}}{\pi k r \sqrt{r}} \int_{R_H}^{R_K} M(r')[-Q'_{k-1/2}(x)] \begin{pmatrix} \sin k\frac{r'}{\lambda} \\ \cos k\frac{r'}{\lambda} \end{pmatrix} \frac{h(r')}{\sqrt{r'}} dr'.$$

In these expressions $Q'_{k-1/2}(x)$ is the derivative of the spherical Legendre function of the II kind from the argument

$$x = \frac{[h(r')]^2 + r^2 + r'^2}{2rr'}, \quad k = mN \ (m = 1, 2, 3 \ldots).$$

If $R \to \infty$, then at $r \to \infty$ the amplitudes of the harmonics trend toward boundary values equal to the amplitudes of the harmonics in the expansion of the field of an infinite system of rectilinear shims,

$$H_m = 8M\frac{1}{m}\sin mN\frac{\alpha}{2}\{e^{-2\pi\frac{h_1}{l}} - e^{-2\pi\frac{h_2}{l}}\}, \tag{5}$$

where H_m is the amplitude of the corresponding harmonics of the field and ℓ the distance between the shims.

For an approximate calculation of the variation of the field of spiral shims in the interval of the radii $R_H \leqslant r < R_K$ one has to equate in formula (5) $\ell = \frac{2\pi\lambda}{\sqrt{1 + (\frac{N\lambda}{r})^2}}$. Calculations which have been carried out after the formulae (3) and (5) show that the approximate formula (5) can be used with sufficient accuracy for the determination of the amplitudes of the harmonics of the field of spiral shims.

For a calculation of the magnetic field variation by the above formulae and the determination of the fundamental parameters of the magnetic system of the cyclotron one has to know the distribution of the magnetization of spiral shims along the radius. This distribution can be found by a calculation of the demagnetizing factor and the magnetization curves. The determination of the magnetization with the required accuracy by the given method, however, is complicated by the circumstance, that in the first place the system is located in a highly heterogenous magnetic field, secondly the spiral shims possess a variable curvature, thickness and height and thirdly there exists an essential mutual influence between the shims. Hence, the parameters of the magnetic system of the cyclotron were made more precise by modeling of its separate components.

The principal parameters of spiral shims have been found on the basis of an investigation of the magnetic field of the system of rectilinear shims. The optimum values of the parameters α and λ have been chosen from the condition of a derivation of the required magnitude of the variation depth on the extreme radii of the accelerator at the maximum gap between the spiral shims. These investigations showed, that with the parameters of spiral shims $N = 8$, $\lambda = 7.7$ ohm, $\alpha = 18^o$ and the minimum permissible gap between the shims $2h_1 \approx 15$ cm one can obtain a variation depth of approx. 25 - 30%. In order to be able to accelerate protons to the energy 700 Mev at such a variation, it is indispensable to choose the diameter of the pole of the electromagnet as equal to 700 cm. Then for the extreme operating radius of the accelerator $r_k = 325$ cm the required magnitude of the amplitude of the 8-th harmonics is equal to $H_8 = 3760$ oersted ($\epsilon = 0.273$) at $H(r_k) =$ 13773 oersted. The profile of the system of spiral shims $h_1(r)$, which safeguards the required law of the change of the field variation along the radius has been found from experiments with rectilinear shims which simulate the parameters of spiral shims on different radii.

The finite radius of the system of spiral shims $R_k = 335$ cm has been derived from the corelation $R_k \approx r_k + \frac{\pi\lambda}{2}$, which was found from the condition for the derivation of the maximum amplitude of the variation on the extreme radius of the accelerator. The interval of the radii $\Delta r = 335 \div 350$ cm is used for the mounting of finite circular shims which permit the formation of the required gradient of the average magnetic field on the extreme radii of the cyclotron.

The parameters of the spiral shims and the profile of the electromagnet pole pieces were made more precise by means of a modeling of the magnetic cyclotron system in the gap of the electromagnet with a pole diameter of 115 cm at a similarity coefficient $K = 1/6.087$. The accuracy of the derivation of the different model parameters amounted to 0.05 - 0.5 mm.

Fig. 1 shows the model of the magnetic system of the cyclotron. Stainless steel disks were used as chamber covers on whose internal side the spiral shims were mounted (fig. 2), whereas on the external the current coils were attached. The chamber was positioned in the gap of the electromagnet, whose poles were domeshaped.

Preliminary studies of the field of the model showed, that the chosen parameters of the magnetic system safeguard the required law of the change of the field variation within the limits of tolerances, with the exception of the finite radii. The average magnetic field is also close to the resonance law except for the central area ($\Delta r = 0 \div 24$ cm), where the field increase over the resonance law amounted to approx. 2000 oersted.

A further forming of the given magnetic field was materialized by a slight change of the profile of the pole pieces $h_M(r)$, the parameters

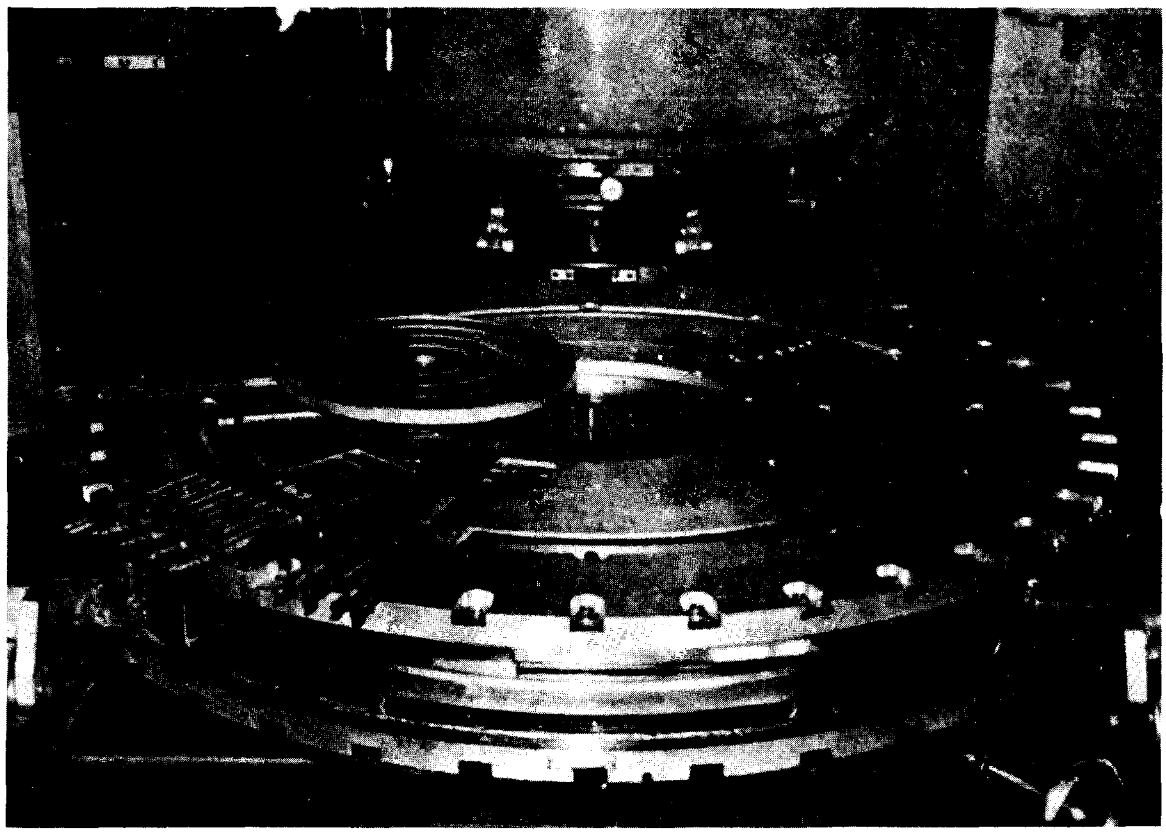

Fig. 1. Chamber and electromagnet of the model of the magnetic system.

of the system of spiral shims $h_1(r)$, $h_2(r)$ and of the gap between the

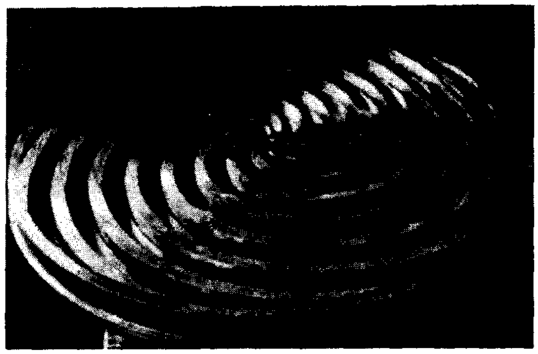

Fig. 2. Chamber cover with the system of spiral shims.

finite circular shims. The topography of the magnetic field was measured with an instrument based on the Hall effect, whose accuracy was $\pm 5 \times 10^{-4}$. The pickup of the magnetometer was attached to a measuring rod which safeguarded its positioning by the radius, azimuth and the vertical with an accuracy of $\pm$ 0.1 mm, $\pm 0.01^{\circ}$ and $\pm$ 0.5 mm respectively. The precise separation of the average field and the amplitude of the basic harmonics from aximuthal measurements over 48 points was $\pm(10 \div 15)$ oersted.

The results from the last stage of the field formation on the model of the magnetic system of the relativistic cyclotron are shown on fig. 2 of the report presented at the Conference [1](see page 550). At this stage of modeling the maximum deviation of the average magnetic field H(r) curve (1) from the resonance field does not exceed $\pm$ 50 oersted, except for the central area. In this area a forming of $\bar{H}(r)$ without a disturbance of the character of the variation can be carried out by current shimming (curve 3 has been obtained by using current coils). The dependence of the amplitude of the 8-th harmonics of the magnetic field on the radius for the profile of the spiral shim system shown on the same fig. is described by curve 2.

It should be mentioned, that for finite radii there exists a deviation of the phase of the basic harmonics from the linear dependence $\varphi = \frac{r}{N\pi}$. By considering the increase of the essential field variation because of this effect, the maximum increase of the required amplitude of the basic field harmonics on the model of the magnetic system amounts to 140 oersted per r = 53.4 cm. For initial radii the curve of the variation satisfies the given requirements, where the intersection of the curve $H_8(r)$ with the line $\epsilon_{min}(r)\ H(r)$ which corresponds to $Q_r = 0$ (Q_z is the frequency of axial oscillations) is located on the radius r = 4 cm. This means, that for the relativistic cyclotron the axial focusing of particles will start from a radius of r = 24 cm.

Hence, the configuration of spiral shims and of the electromagnet pole pieces has been found on the basis of the results obtained from the field formation on the model, which permits to generate a magnetic field close to the assigned one in the median plane.

Literature cited

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2. D. P. Vasilievskaya, A. A. Glazov, V. I. Danilov, Yu. N. Denisov, V. P. Dzhelepov et al. "Atomnaya Energiya", 8, 189 (1960).
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Discussion

P. Lapostolle

1. What is the spiral angle? Is there no harmful non-linear effect to expect?
2. Why did you not consider the resonant extraction scheme which is usually considered as very efficient? Do you expect better results with your schemes?
3. If a decision is made for converting your machine to spiral ridge focusing how long would it take to achieve the modification?
4. What are the vacuum gasket you intend to use in order to avoid radiation damage?

V. P. Dzhelepov

1. The minimum spiral angle on the extreme radius (the angle

between the spiral and vicinity) is 11°. The non-linear effects were critical at the choice of the structural parameters of the magnetic field. One of the non-linear resonances at $Q_r = 1$ has been studied experimentally by us on the model of the spiral cyclotron at $N = 4$. An essential influence of this effect upon the translocation of orbit centers has been established.

2. It is not possible to generate energies higher than 700 Mev on our accelerator under the conditions of a utilization of the magnet available from the synchrocyclotron. Here the frequency of radial oscillations reaches only 1.8, which does not permit to use the resonance method. We hope that during the materialization of extraction methods under development in our Laboratory, we will achieve an extraction coefficient up to 90%.

3. I believe, that after the additional buildings will have been erected and the new equipment installed the actual reconstruction should take approx. 1 1/2 years.

4. We intend to use rubber linings as vacuum gaskets in places where the radiation fluxes are not too high. In some cases in most strongly activated areas metallic gaskets will be used.

M. Barbier

Will you use external targets only or also internal targets?

V. P. Dzhelepov

As a rule, at the operation of the accelerator at high voltages external targets will be used. Internal targets will be used during the adjustment and investigation of the accelerator, the current, however, will be specially decreased to the order of approx. 1 microampere.

R. S. Livingston

1. Could you comment on the number of sectors?
2. What efficiency of deflection do you hope for?
3. How much will the cyclotron conversion cost?

V. P. Dzhelepov

1. The choice of the number of spirals is determined essentially by the condition of a safeguarding of the passage of particles through the resonances. Calculations showed, that for a transit through the most dangerous internal resonance of the fourth order N must be greater than the fourfold maximum frequency of radial oscillations:

$N > 4Q_r = 7.2$, since in our accelerator $Q_{r\ max} = 1.8$. On the other hand, the number of spirals should not be too high, since with an increase of N the required magnitude of the field variation increases ($\epsilon \sim \frac{N\lambda}{r}\sqrt{n}$, as is known) and the generation of a high variation at the conditions of a cyclotron type magnet is a very difficult problem. For these reasons we chose N = 8.

2. Approx. 90%.

3. According to preliminary estimates the costs of the project presented in our report will amount to 15 - 18 million rubles.

R. R. Wideröe

Have you made any experiments with the extraction system?

V. P. Dzhelepov

We performed experiments on the beam extraction on a model with six spirals in 1962 and obtained an extraction coefficient of approx. 40%. This, however, cannot be applied directly to a large accelerator for which different extraction methods are being developed.

C. S. Taylor

Have you given any consideration to radiation damage, even to components normally considered insensitive to radiation with the high beam power proposed?

V. P. Dzhelepov

As far as the magnetic and mechanical properties are concerned this will not be a problem in the relativistic cyclotron as can be gathered from special experiments carried out in our Laboratory. The most serious problem will be the insulation of magnetic coils.

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