SOME FEATURES OF GRADIENT CORRECTION IN THE ITEP PROTON SYNCHROTRON

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1. INTRODUCTION

The ITEP proton synchrotron focusing system (L-1) has the magnetic blocks of three types: radially focusing (F-blocks), radially defocusing (D-blocks) and radially focusing quadrupole lenses (X-blocks). The magnetic blocks form 14 superperiods, 8 blocks in the each. The magnetic blocks installation scheme within the period and their numeration are given in Fig. 1. In the same figure the numeration of points used in calculations is given.

In the main design regime the gradient in the X, F and D-blocks was chosen to be equal; the r and z betatron oscillation frequencies (Q_r and Q_z) being equal to each other and, at the design value of the momentum, having the value of 12.75. Due to the difference between the magnetic blocks the gradient in the accelerator blocks at the moment of injection is not equal to its design value. Three correcting coil systems have been installed to correct the gradient.

Changing the currents within these coils (J_x, J_F and J_D) makes it possible to change the betatron oscillation frequency, the frequency Q_z being mainly determined by the value of J_D and the frequency Q_r by two currents J_x and J_F. Due to the resonance character of the accelerator's magnetic structure the choice of the ratio between J_x and J_F currents (and, consequently, between the gradients in the X and F-blocks) affects considerably the Floquet-function and the ψ-function (L-2). The resonance character of magnetic structure is due to the fact that the number of X-blocks is close to the betatron oscillation frequency. Note that similar effects will take place in any strong-focusing accelerator where the number of superperiods of magnetic system m satisfies the equation:

$$mN \approx Q \qquad [1]$$

where N is an integer.

In such accelerators it is possible to change the Floquet-function and the ψ-function in a rather wide range by changing the ratio of the currents in the gradient correction systems.

2. EXPERIMENTAL INVESTIGATION OF CAPTURE COEFFICIENT

The ratio between J_x and J_F currents affects the main parameters of the accelerator, and therefore this ratio should be expected to affect the coefficient of particles capture into the acceleration regime — K. To get the optimal ratio between the currents J_x, J_F and J_D the dependence of K on the current J_x was experimentally studied, for each value of J_x the currents J_F and J_D having been chosen to get the maximum value of K. The graph of dependence of K on J_x experimentally obtained is given in Fig. 2. The measurement of betatron oscillation frequencies has shown that for all J_x the currents J_F and J_D were chosen so that betatron oscillation frequencies remained constant and equal to each other. However, in spite of the frequencies constancy, the value of K reveals a considerable dependence on J_x.

To compare the results of the experiment with the theory it is necessary to find out which value of the current J_x corresponds to the nominal working regime of the accelerator. It can be easily seen that in the nominal regime the current J_D must be equal to the current J_F. Indeed, in the nominal regime the gradient in F-blocks is equal to the gradient in D-blocks; due to the identity of F- and D-blocks and their gradient coils the equality of currents follows from the equality of gradients Hence it has been found that the following values of currents correspond to the nominal regime: $J_F^\circ = J_D^\circ = -1{,}0$ A, $J_x^\circ = 1{,}75$ A.

3. CALCULATION OF FLOQUET-FUNCTION AND OF ψ-FUNCTION AT VARIOUS DISTRIBUTION OF GRADIENTS

When gradients in X- and F- blocks are chandged that is not only the betatron frequency but also the value of the 28-th harmonic of the field gradient which is varied. This results in the strong dependence of the radial Floquet function φ_r on the gradient deviations $(\Delta G/G)_x$ and $(\Delta G/G)_\Phi$ in X- and F-blocks correspondingly.

The Floquet-function can be found from equation

$$r'' + \omega^2(x)\left[1 + \left(\frac{\Delta G}{G}\right)_x g_x + \left(\frac{\Delta G}{G}\right)_\Phi g_\Phi\right] r = 0, \qquad [2]$$

ψ-function is determined from the following equation

$$\psi'' + \omega^2(x)\left[1 + \left(\frac{\Delta G}{G}\right) g_x + \left(\frac{\Delta G}{G}\right)_\Phi g_\Phi\right]\psi = \frac{1}{R(x)} \qquad [3]$$

where $\omega^2(x) = \frac{dH_z}{dr}(x)\cdot\frac{1}{HR}$, $R(x)$ is the radius of curvature, x is the distance taken along the equilibrium orbit, g_x and g_Φ are the step functions, equal, respectively to 1 in X- and F-blocks, and to zero in the rest of them. The eqs. [2] and [3] were solved for different values of $(\Delta G/G)_x$ and $(\Delta G/G)_\Phi$ on the computer M-20 using the methods described in L-2. Let us note that the beam dimension and, consequently, K are affected by the variations of modulus and not by the phase of the Floquet-function. At small deviations of the gradient the value of ψ-function and of Floquet-function modulus can be estimated using the approximated linear formulae

$$\left.\begin{aligned} \Delta|\varphi_r| &= \alpha_x\left(\frac{\Delta G}{G}\right)_x + \alpha_\Phi\left(\frac{\Delta G}{G}\right)_\Phi \\ \Delta\psi &= \Gamma_x\left(\frac{\Delta G}{G}\right)_x + \Gamma_\Phi\left(\frac{\Delta G}{G}\right)_\Phi \end{aligned}\right\} \qquad [4]$$

In the Table I the values α_x and α_Φ for different points of the focusing system are given. The values of these coefficients at the points corresponding to the second half of the magnetic period are symmetrical relative to the zero index point. The values of α_x and α_Φ have been found using the numerical solution of the eq. [2]. The values Γ_x and Γ_Φ are given in (1-2), Table I.

At considerable deviations of the gradient the linearized equations give an essential error. To determine the precise values of ψ-function and the Floquet-function the eqs. [2] and [3] were solved numerically for different values of $(\Delta G/G)_x$; $(\Delta G/G)_\Phi$ being chosen so that Q_r remained constant.

In Fig. 3 the graph of the dependence of $|\varphi_r|$ and ψ-function on $(\Delta G/G)_x$ for the most important points of the magnetic system — the middles of the focusing blocks is plotted. It is seen from this figure that when $(\Delta G/G)_x$ decreasing the Floquet-function modulus at the points 0 and 16 begins to decrease and at the point 8- to increase; maximal Floquet-function determining the acceptance of the chamber decreases. This decreasing of the modulus is due to the fact that in the nominal regime the Floquet-function modulus is modulated by the 28-th harmonic when $(\Delta G/G)_x$ is changed; the appearing of 28-th harmonic conpensates this modulation.

The comparison of exact solution plotted in Fig. 3 with the approximated formulae [5] shows that though the Floquet-function is described well enough by these linearized equations, the ψ-function changes non-linearly.

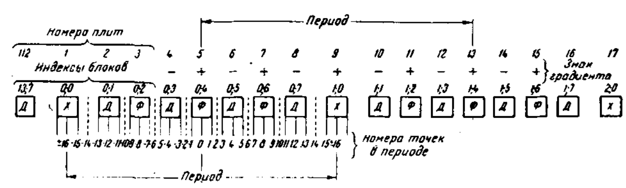

Fig. 1 - The magnetic blocks installation scheme.

TABLE I

N	0	1	2	3	4	5	6	7
α_x	8,16	5,91	5,52	4,86	0,88	— 3,28	— 3.97	— 4,44
α_Φ	— 6,10	—4,75	— 4,60	— 4,42	— 2,70	0,37	0,57	1,01

N	8	9	10	11	12	13	14	15	16
α_x	— 6,85	— 5,95	— 5,72	— 5,26	— 2,64	2,42	3,10	3,72	5,75
α_Φ	3,02	2,38	2,10	1,41	— 0,40	— 2,10	— 2,76	— 3,02	— 4,48

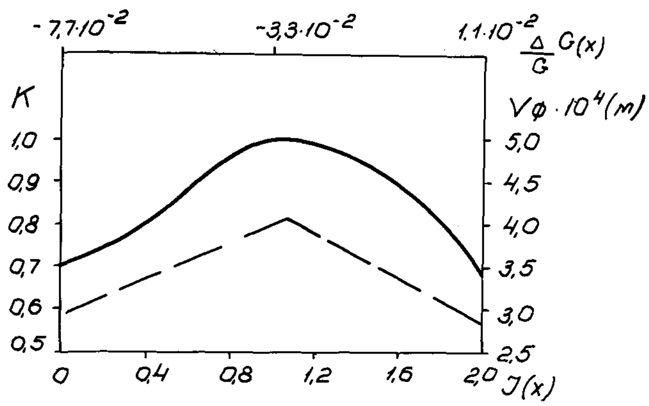

Fig. 2 - The graph of dependence of K (the solid curve) and of V (the dotted curve) on J_x current. The values of $(\Delta G/G)_x$ corresponding the values of I_x are given above. Maximum value of K is equal to 1,0.

The behaviour of ψ-function is seen from the approximated analytical solution which can be obtained by considering X-blocks as thin lenses. It follows from this solution that (when $(\Delta G/G)_x$ being changed) the main terms of the expansion of ψ-function into Fourier series, the constant and the 14-th harmonic, behave as follows:

1) the value of the constant nearly independent on $(\Delta G/G)_x$;

2) the amplitude of the 14-th harmonic a_{14} changes according to the formula

$$\Delta a_{14} \approx \frac{\psi_0 \tilde{g}}{\tilde{g} + Q + 14} \qquad [5]$$

where $\tilde{g} \approx 15\ (\Delta G/G)_x$ is the width of the 28-th harmonic of the half-integer resonance, ψ_0 is the value of the ψ-function in the middle of X-block at nominal conditions. The formula [6] shows that the deviation of the gradient in X-blocks, from the stand-point of affecting the ψ-function, is equivalent to approaching the betatron frequency to 14.

4. COMPARISON OF EXPERIMENT AND THEORY

It follows from the Fig. 3 that K is maximum at the gradients in X-blocks, somewhat less than its design value. Indeed, the maximal Floquet-function modulus has the minimum at $(\Delta G/G)_x < 0$; on the other hand, the maximum od ψ-function also decreases when the gradient in X-blocks is decreasing. To compare with the experiment the theoretical estimation of dependence of K on the gradient in X-blocks is of interest. It can be expected that the value of K is proportional to the acceptance of the accelerator V which is determined by the formula

$$V = \frac{[A - \psi(\frac{\overline{\Delta p}}{p})]^2}{|\varphi_{max}|^2} \qquad [6]$$

Here A is the halfwidth of the vacuum chamber $(\overline{\Delta p}/p)$ is the mean momentum spread of the beam. $(\overline{\Delta p}/p)$ was assumed to be equal to $3 \cdot 10^{-3}$. The theoretical plot of dependence of on J_x is given in Fig. 2. The value J_x corresponding to the given values $(\Delta G/G)_x$ could be found by known values of J_x^0, J_Φ^0 and J_D^0. It is seen from J_x is close to the plot of dependence of K on on J_x is close to the plot of dependence of K on J_x. This allows to make a conclusion that the mechanism of affecting the capture by the gradient coils proposed is, apparently, correct.

Acknowledgement

The authors are indebted to L. L. Goldin for numerous valuable remarks and to O. N. Vasilyeva for calculations.

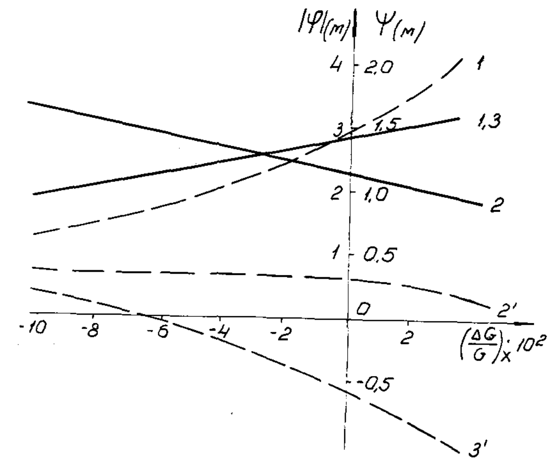

Fig. 3 - The graph of dependence of Floquet function modulus (the solid curves) and ψ — function (the dotted curves) on $(\Delta G/G)_x$. The curves 1,1' — correspond to the 16-th point of magnetic period, 2,2' — to the 8th point, 3,3' — to zero point.

REFERENCES

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(2) Tarasov, E. K.: PTE No. 4, p. 141 (1962).

DISCUSSION

COURANT: Your diagram showed that even with the correction the radial field still varied with radius. This should not eliminate the coupling between horizontal and vertical , oscillations, but shift the equilibrium orbit. Have you also attempted to reduce the slope of this curve, so as to make B_r equal to zero everywhere on the machine plane?

KOTOV: In the figure it is shown the radial field component B_r in 4 D-blocks, in which are the correcting coils. In the presence of such a field component in the 4 D-blocks, the mean value of B_r along the perimeter of the accelerator is near to zero and then the coupling between the betatron frequencies disappears.

ZGS PERFORMANCE AND IMPROVEMENT PROGRAM *

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The first beam accelerated to about 5 GeV in the Argonne Zero Gradient Synchrotron was reported two years ago at the Dubna International Conference for High Energy Accelerators. Since that time, the ZGS has reached a top energy of 12.7 GeV and a peak intensity of about 8×10^{11} protons/pulse. The ring magnet and power supply have been operating very reliably at a maximum repetition rare or 24 min^{-1} without flat-top or 17 min^{-1} with 250 ms flat-top.

During the shakedown period in the early part of 1964, the most troublesome difficulty encountered was in the vacuum system. The ZGS has a double vacuum system with an outer rough vacuum chamber formed by the magnet yoke and a thin-walled inner high vacuum chamber. Before the vacuum control and protective interlock systems were adequately debugged, some operational error led to an accidental loss of the outer vacuum and collapsed the inner vacuum chambers in three ring magnet octants. A couple of months were spent in repairing these chambers, installing rupture diaphragms, and modifying the vacuum control and interlock logics. The vacuum system has since been in trouble-free operation.

* Work performed under the auspices of the U. S. Atomic Energy Commission.

Very little trouble was encountered in the operation of the 50 MeV linac injector. The focusing quadrupoles in the drift tubes are still operating in the + — + — mode. The linac normally produces a beam of about 20 mA at a pulse duration of 150 μs and an emittance of about π mrad-inch. Some arc-down difficulties were encountered in the 750 kV Cockcroft-Walton preaccelerator. This was traced to the field distortion caused by the dielectric rods which are used to control the ion source inside the high voltage terminal and which were set right next to the accelerating column and inside the voltage dividing rings. These control rods were moved to a position perpendicular to the accelerating column. This eliminated the arc-down troubles. During part of the ZGS maintenance period, the linac is available for beam studies. We have been studying the dependence of the energy distribution and the emittance on the preaccelerator voltage, the linac r.f. level and flatness, and the buncher voltage and phase. Minor improvements are being made on the r.f. system of the linac, such as the addition of closed-loop feedback circuitry to maintain the r.f. level during beam loading. We are also modifying the preaccelerator voltage regulation system and working on a development program with MURA for a high current ion source and a doubly re-