RESEARCH OF THE BEAM ORBIT EXPANSION EFFECT

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Summary

This paper deals with theoretical and experimental investigations of the beam orbit expansion effect in cyclotrons with a spatial variation of the magnetic field. More accurate expressions for the tolerances of the magnetic field and parameters of the beam are given. Methods to achieve those tolerances in the experimental accelerator-electron model of a cyclotron and experimental results are described.

The Joint Institute for Nuclear Research is a leading world centre in developing and constructing cyclotrons for scientific research and practical application and in developing the theory of the cyclotron method of acceleration. The construction principle for cyclotrons with higher average magnetic field has been suggested and realized in the U-200 heavy ion cyclotron in Dubna.[1] In 1978 the same basis was employed for the largest heavy ion cyclotron U-400[3]. In 1971 the world first two-cyclotron complex with a charge-exchange beam injection from one cyclotron to the other was put into operation on the basis of U-200 and U-300 cyclotrons[2].

Besides the construction of heavy ion cyclotrons with radial-sector focusing, theoretical and experimental work on relativistic cyclotrons is being pursued in Dubna. In 1959 the world first cyclotron with a spiral structure of the field, the 120 cm diameter operating model of the 700 MeV relativistic cyclotron[4], was put into operation. A spiral structure of the magnetic field was used in cyclotron U-120 M[5]. In 1968 an electron model of the relativistic circular cyclotron (EMCC) was built to study the effects occurring during acceleration of the beam with a large space charge[6]. Experiments at this facility showed a possibility to accelerate beams with current corresponding to 100 mA in a proton accelerator. Since highly effective beam extraction at these currents is of special importance, the effect of orbit expansion in periodical magnetic structures, discovered by Prof. V.P. Dmitrievsky with coworkers in 1972[7], has been studied in JINR theoretically and experimentally for about ten years.

The results were published in many communications and presented at conferences in Dubna[8], Washington[9] and Caen[10]. In short, the effect is as follows: for a field which is periodical in a symmetry plane and has the form

$$B_Z = \bar{B}(R) + \sum_{k=1}^{\infty} B_{KN}\cos[\beta_{KN}(R) - KN\varphi] \qquad (1)$$

there are periodical solutions of the equations of motion (orbits) for a discrete set of momenta $p_i = eB(R_i)R_i\lambda$ separated from each other by a distance

$$\Delta R = \alpha \frac{\Delta p}{p_i} R_i \qquad (2)$$

where α is the momentum compaction factor and λ is a dimensionless quantity defined by the field structure.

For field (1) the compaction coefficient is

$$\alpha = (1 + n + \frac{R}{\lambda}\frac{d\lambda}{dR})^{-1}. \qquad (3)$$

The expression for λ is obtained from the equations of motion:

$$\lambda \approx 0.5 + \left[0.25 + \frac{B_N^2(1.5+n_N)}{2N^2\bar{B}^2}\right]^{1/2}, \quad n_N = \frac{R}{B_N}\frac{dB_N}{dR}, \qquad (4)$$

and from (3) and (4) it follows (within a few per cent) that

$$\alpha \approx \left[1 + n + \frac{B_N^2}{2N\bar{B}^2}\left(n_N^2 + \frac{R^2}{B_N}\frac{d^2B_N}{dR^2}\right)\right]^{-1} \qquad (5)$$

For a given energy gain per turn, we can increase ΔR in equation (2) by increasing α. This can be done by making the first and second derivatives of $B_N(R)$ negative.

The magnetic field parameters necessary to achieve the chosen orbit expansion can be computed from the set of equations (3) and (4), where α is the given function and the mean field $\bar{B}(R)$ is taken from the experimental data.

The first experimental investigations of the expansion effect at EMCC showed a ten-fold increase in orbit separation (up to 30÷40 mm), but at the same time the radial size of the beam cross section extended. Further calculations showed that this can be due to discontinuities in the orbit expansion coefficient as a function of radius, due to imperfections in the variation field. Now the variation decreasing coil is supplemented with three pairs of similar coils installed closer to the median plane[11].

Fig. 1 shows the dependence of the amplitude of the variation fundamental harmonic (N=8), as well as calculated and experimental dependences of the expansion coefficient $K=\alpha(1+n)$ for EMCC with a modified magnetic system. It is seen that the obtained function K(R) is a continuous one, and the maximum value of the coefficient corresponds to eightfold-tenfold increase of the orbit energy step.

Numerical calculations showed that coherent beam oscillations in the expansion zone should not exceed 5

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mm, and that the amplitudes of the lower harmonics of the axial magnetic field components B_1, B_2 should be below 2×10^{-3} (0.05 Gs). To meet these requirements, a system of correcting coils is installed in EMCC, which allows changing the amplitude and phase of the lower harmonics in the whole acceleration region.

To reduce the amplitude of coherent beam oscillations, one 90-degree dee is replaced by two 45-degree dees, placed opposite to each other and excited in antiphase.

The result of energy spread is a wider beam in the expansion zone and, consequently, an obscure effect. The quantitative estimate in Ref. 10 shows that a relative energy spread for EMCC should be $\sim 10^{-3}$. For acceleration with the sinusoidal field, the spread $\delta W = 10^{-3}$ at the maximum gain corresponds to a phase extent of 5°, which corresponds to a bunch time in EMCC of 0.35 ns. To achieve such duration for an injection bunch an injection system with high-frequency extraction and acceleration voltage, and beam collimation on the first turn has been developed. The collimation is done by two diaphragms with $\Delta R = 0.5$ mm placed at the azimuth 90° and 180° to the injector.

Fig. 2 shows the experimental results on suppression of coherent beam oscillations at initial radii by means of harmonic coils. It is seen that coherent oscillations at radii up to 40 cm are reduced from 4 cm to 0.5 cm by selecting appropriate currents in the coils.

It follows from the experiments that the amplitude of coherent beam oscillations at all radii of EMCC does not exceed 5 mm, i.e. it is within the tolerance obtained from the computer analysis of the expansion effect. The amplitude of non-coherent oscillations does not exceed 4-5 mm as well. Investigations of the beam phase motion during acceleration have shown that the mean field cannot be shaped with the necessary accuracy, and there is a 10-degree phase shift which causes an intolerable energy spread[12].

In this situation the only possible way to get an accelerated beam with a tolerable energy spread is the flat-top mode of acceleration[13].

It has been decided to use the set of the first and second harmonics of the accelerating voltage because, owing to construction peculiarities of the model, acceleration is possible only with dees whose length is near the working wave-length, even for the fundamental harmonic of the accelerating voltage. The result is a marked radial distribution of the voltage.

If the first and second harmonics of the accelerating voltage are used at optimum phase correlations, energy gain per turn is

$$\Delta W/\Delta W_{oi} = \cos\varphi - \frac{1}{a}\cos 2\varphi , \tag{6}$$

where ΔW_{oi} is defined by the accelerating voltage amplitude U_{oi} and by the dee phase length $q\theta_i$:

$$\Delta W_{oi} = 2U_{oi} \sin q\theta_i/2, \quad a = \Delta W_{o1}/\Delta W_{o2} . \tag{7}$$

The optimum value of energy gains on the dees of the first and second harmonics $a \approx 4$ can be kept by varying the angular length of the dee of the second harmonic θ_2. Assuming that the dee of the second harmonic at R=105 cm has an angular length equal to the angular length of the dee of the first harmonic (45°), we get for a=4

$$\sin\theta_2 = 0.25 \frac{U_{o1}}{U_{o2}} \sin 22.5° \frac{U_1(R)/U_{o1}}{U_2(R)/U_{o2}} , \tag{8}$$

$$\frac{U_{o1}}{U_{o2}} = 8\cos 22.5° \frac{U_2(105)/U_{o2}}{U_1(105)/U_{o1}} , \tag{9}$$

where U_{o1} and U_{o2} are the voltages of the first and second harmonics in the centre for R = 15 cm.

Voltage distribution $U_1(R)$ for the first harmonic can be found from an experiment with the real dee, and initial distribution for the second harmonic $U_2(R)$ from calculations or an experiment with a 45-degree dee on the second harmonic.

The results of the measurements of the voltage distributions $U_1(R)$, $U_2(R)$ and calculation of the second harmonic dee profile by means of expressions (7), (8) are shown in Figs. 3 and 4.

The value obtained for a for $U_{o1}/U_{o2} = 3.2$ is within the limits $3.850 \leq a \leq 4.018$, which corresponds to $44.8° \geq \Delta\varphi(a) \geq 30.3°$.

To employ the flat-top mode of acceleration a sophisticated instrumentation system has been developed and manufactured in addition to that of the electron model.

Tentative experiments with the electron model showed that the developed complex for flat-top acceleration provides a markedly better regime for current flow with orbit separation practically to the final radius, as well as an effective orbit separation at the extraction radius (Fig. 5).

In future it is planned to increase the power of the HF amplifier of the second harmonic in order to ensure wider possibilities of the system in experimental investigations and achieve higher stability in operation.

References

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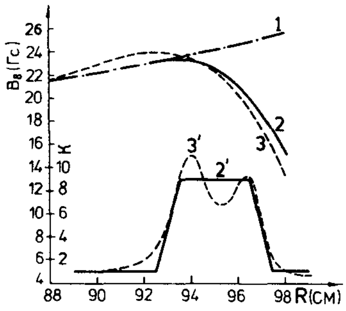

Fig. 1.

Parameters of the magnetic field in the beam orbit expansion zone:
1 - initial meaning $B_8(R)$, 2,2' - calculated and 3,3' - measured dependences $B_8(R)$ and K(R) in regime with expansion.

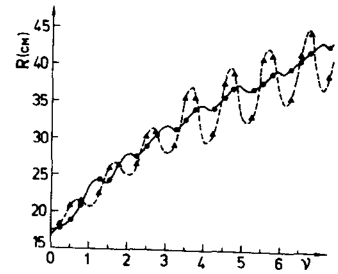

Fig. 2.

Suppression of coherent beam oscillations: triangles - initial and points - final orbits position in dependence on turn number.

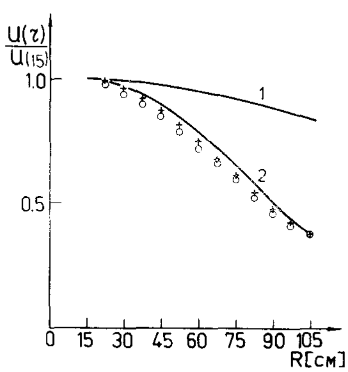

Fig. 3.

Voltage distribution along the dees for first and second harmonics: solid lines - 45° dees, crosses - first approximation, circles - final.

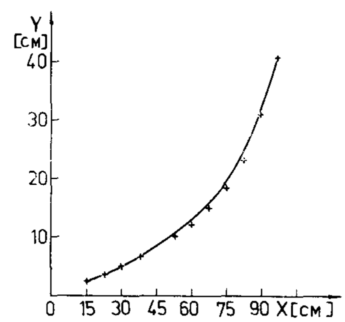

Fig. 4.

Second harmonic dee profile. Crosses - first approximation.

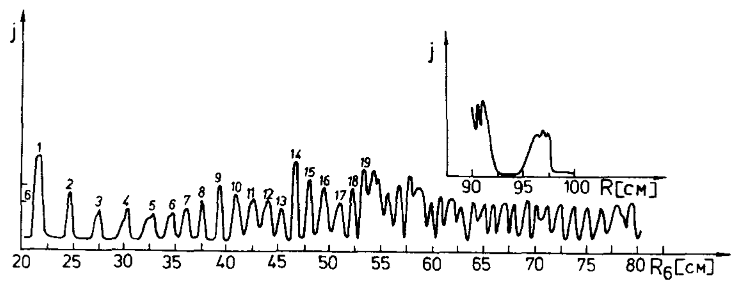

Fig. 5.

Current density distribution along the radius.