THE SYSTEM OF AUTOMATIC BEAM PHASE MEASURING AND CONTROL FOR THE ISOCHRONOUS CYCLOTRONS

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Abstract

The system of automatic measuring and control of the phase of a beam passing through as accelerating field in an electron cyclotron is described. The system has been performed on the base of a digital control computer. The beam phase at different radii of the cyclotron is measured by inductive magnetic pick-ups. The signals, sensed at the pick-ups, are introduced into the computer after conversion in a sampling oscilloscope. The mean deviation of the beam phase distribution over the radii from the desired status amounted to 2-3°. Having used this system, the automatic leading of the beam through the cyclotron was realized. The beam, which had initially reached only the first pick-up, was automatically led to the final radius ofacceleration.

1. Introduction

The system has been tested at the electron isochronous cyclotron with strong focusing located at the Laboratory of Nuclear Problems, JINR[1]. Electrons injected onto a radius of 18 cm from the external source are accelerated up to a radius of 100 cm. The final energy amounts to about 500 keV.

The magnetic field of the cyclotron is completely formed by a system of coils without iron. Information about the phase of the beam bunches passing the 90° Dee is sensed at 12 inductive magnetic probes[2], located in a cyclotron chamber at radii 55-59 cm with a step of 4 cm. The correction of the magnetic field is done by means of 8 concentric coils, located along all the range of acceleration, staggered at distances 10 cm one from the other. The increments of the currents are set in power supplies through 8-bit digital-to-analog convertors. The control computer is an M-6000 with 8K of 16-bit of 2.5 microsecond core memory[3].

2. Measuring of the beam phase

The block diagram of the beam phase measuring is shown in Fig. 1. The system can operate in three modes:

1) mode of observation;

2) mode of calibrating display;

3) mode of data input and processing in the CPU.

The observation allows the phase signals, sensed at the pick-ups as well as the signal of accelerating RF voltage to be checked visually on an oscilloscope screen. It is possible to estimate approximately the beam phase distribution versus radii.

The mode of calibrating display is used for setting the measuring equipment.

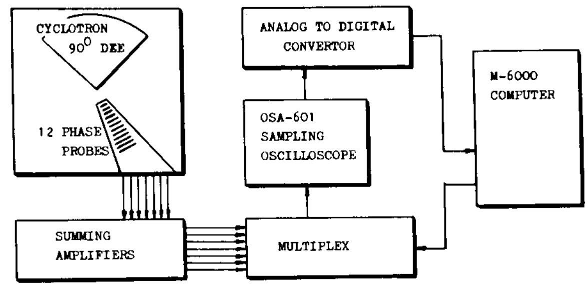

Fig. 1 Block diagram of the beam phase

In the mode of data input and processing in the CPU, the signals induced at the pick-ups by the beam and a reference signal taken from the accelerating RF voltage follow through a multiplex to the input of a sampling oscilloscope OSA-601. The amplitudes of the sampling pulses are converted to the digital codes which are stored in the core memory of the control CPU. These data are used for computation of the phase according to either geometrical form of the signal or the method of harmonic analysis.

By the geometric method the beam phase is determined according to the formula

$$\Phi = \frac{X_F - X_A}{X_B - X_A} - \theta \ , \qquad (1)$$

where (see Fig. 2) X_A is the coordinate of crossing the zero line and the rising part of the sinusoidal Dee voltage wave. X_B is the coordinate of crossing the zero line and the falling part of the Dee voltage. X_F is the coordinate of crossing the zero line and the signal from the pick-up. θ is the angle between the axis of symmetry of the Dee and the pick-ups.

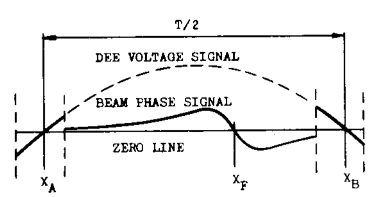

Fig. 2 Mutual distribution of signals for the geometric method of determination of the beam phase.

Using the maximum sampling density of 500 samples per sweep and applying linear interpolation between the samples, an accuracy of better than 0.1° in determination of the phase may be obtained. In real conditions the accuracy will be worse due to sweep non-linearity and the distortions of the shape of signals from the pick-ups which influences the

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shifting of the crossing points. Main causes of the distortion are the limited band-width of a channel between the pick-ups and the input of the sampling oscilloscope and the influence of the Dee voltage induced to the pick-up circuit. The noise of a random type is essentially suppressed by using a multiple input of the same channel into the CPU and subsequent statistical processing. The duration of the input and processing of all 12 channels amounts to 1-10 sec in accordance with the number of input repetition.

Comparable measurements have been done at the electron cyclotron using both the described method and the method of intercepting the beam by a probe. The phase shifting between the signal of the probe and the signal from the Dee RF voltage has been measured by a commercially purchased phase meter. The differences between the results obtained in these measurements are within an r.m.s. of about 2°.

For operation of the system in conditions of high noises, the second method of beam phase determination was developed, based on a separation of the second harmonics of a signal introduced in to the core memory in the CPU. This was was also tested at the electron cyclotron. The accuracy obtained by this way was of the same order as that of the geometrical method.

A common advantage of these two methods consists in the fact that if the frequency of accelerating voltage varies it is sufficient to tune only the sweep of the sampling oscilloscope without changing other parameters of the phase measuring system. This is the reason why the described system is suitable to measure the beam phase in the isochronous cyclotron with variable energy.

3. Mathematical grounds for control algorithm

The block diagram of the beam phase control systemis shown in Fig. 3. The measured deviations of the beam phase distribution over the cyclotron radii from the desired values are used to calculate correction currents set in 8 concentric trim coils. As the time spent for phase measuring at all 12 radii is a hundred times more than the time constants of the trim coils in the accelerator, the cyclotron may be considered as a static multiparameter system without analysing the dynamics of transfer processes.

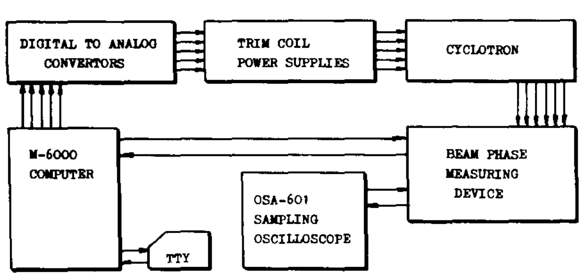

Fig. 3 Block diagram of the beam phase control

For small phase deviations at m radii from the correction current increments in n coils, the system may be described by m linear equations:

$$\sum_{k=1}^{n} G_{ik}\Delta I_k = \Delta \sin \phi(R_i) \qquad (2)$$

where $\Delta \sin \phi(R_i)$ is the desired sine variation of the phase angle at radius R_i; ΔI_k is the correction current increment in the k-th coil. The coefficient G_{ik} for the i-th radius from the k-th coil can be calculated by the formula

$$G_{ik} = -\frac{2\,E_0}{r_\infty^2 \Delta W H_0} \int_{R_0}^{R_i} g_k(r)\cdot S_{(r)}\cdot r\cdot dr \qquad (3)$$

where $g_k(r)$ is the magnetic field of the k-th coil for a current of 1A and radius r; $S_{(r)}$ is the function taking into account the prolongation of the orbit with respect to unit circle; H_0 is the value of the isochronous field in the centre of the cyclotron; E_0 is the rest energy of accelerated particles; ΔW is a maximum gain of energy per turn, $r_\infty = c/\omega$. Since the phase cannot be measured at radii near the injection radius R_0, it is desirable to add Eq. (4) to the system (2) in order to keep the isochronous field at R_0

$$\sum_{k=1}^{n} g_k(R_0)\Delta I_k = H(R_0) - H_S(R_0)\ . \qquad (4)$$

The system of (m + 1) equations obtained from (2) and (4) is used to solve the n variables and as a rule (m + 1) > n. In this case the correction current increments ΔI_k are found by minimizing the functional

$$F = \sum_{j=1}^{m+1} \varepsilon_j^2 + \sum_{k=1}^{n} (\alpha_k \Delta I_k)^2 \qquad (5)$$

where ε_j is the difference between the left and right parts of the j-th equation of the system (2); α_k is an empirically chosen quotient. The insertion of the member with α_k into the functional F somewhat decreases the accuracy of phase correction but, on the other hand, minimizes the magnitudes of current increments ΔI_k. The smoothness of the magnetic field is much better in this case. When the simple least square method is used, the increments can be too large, and consequently the perturbances of the magnetic field can reach not permissible values with respect to the stability of motion of the beam in the process of acceleration. Choosing suitable values of α_k, it is possible to obtain both sufficient smoothness of the magnetic field and satisfactory values of errors in beam phase correction.

Differentiating function (5) with respect to ΔI_k and equating the obtained expressions to zero, the system of n equations is obtained in which any p-th equation may be expressed as

$$\sum_{k=1}^{n} \Delta I_k \left(\sum_{j=1}^{m+1} G_{jp} G_{jk} \right) + \alpha_p^2 \Delta I_p = \sum_{j=1}^{m+1} G_{jp}\ \Delta \sin \phi\ (R_j) \qquad (6)$$

The coefficients G_{ik} can be found either by calculations according to formula (3) or by automatic measurements at the cyclotron using the CPU for operating, measuring and solving the relation $G_{ik} = \partial(\sin \phi(R_j))/\partial(I_k)$. The measured values G_{ik} were found about 30% higher in comparison with the theoretically calculated ones. This difference can be explained by the great azimuthal width of the bunches in the cyclotron during the measuring time as formula (3) is valid for a point charge.

4. Software

Figure 4 shows the set of subroutines for the beam phase control of the electron cyclotron. The program consists of separate parts which are called through the subroutine DISP (Dispatcher) either by an operator or automatically in accordance with the queue of tasks introduced into the memory before operation. The calls of these subroutines are realized according to the labels which coincide with those in the text of the corresponding program written in Fortran. The example of a continuous cycle

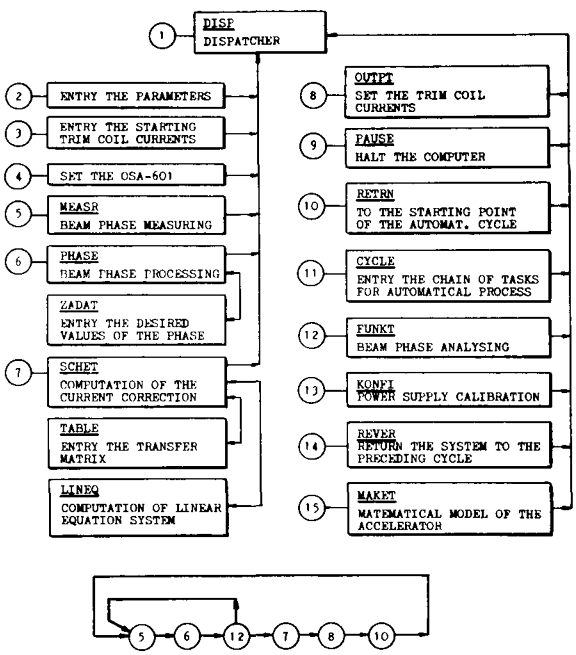

Fig. 4 Set of subroutines for an automatic measurement and control of the beam phase.

is given in the lower part of Fig. 4. Label 5 calls the subroutine of phase measuring. Through label 6 the measured phase is processed and its course versus the radius is compared with that prescribed by subroutine ZADAT. After this, the quality function is calculated, whose value is analysed in subroutine 12. If the function is satisfactorily small, the measurement of the beam phase is repeated in the opposite case the correction is necessary, and the increments of the trim coil currents are calculated in subroutine SCHET (Label 7). New current values are set in the sources by subroutine 8, OUTPT, and label 10 returns the cycle to the starting point 5: measuring of a new phase obtained as a result of correction. The control quality in each cycle is estimated according to the criteria that take into account errors of the phase distribution, the values of current increments and the intensity of the beam versus radii.

5. Obtained results

The beam phase control system described in this paper has been tested in different modes of operation since December, 1974.

The mean value of the phase correction errors (r.m.s.) was about 2-3°. Having used a special strategy in the subroutine PHASE, the beam phase control system was able to lead the beam to the final radius of acceleration during several iterations even in such cases when the beam had initially reached only the radius of the first pick-up. The example of the leading of the beam through the electron cyclotron is shown in Fig. 5. The beam phase is put in the vertical axis. The radius of location of the pick-ups and the consecutive number of iterations, N_{ITER} are put in the horizontal axis. At the initial state, the beam reached only the first pick-up at a radius of 55 cm with a phase of - 35° close to the phase of deceleration. The range of acceleration was extended up to 75 cm after the first correction and after the

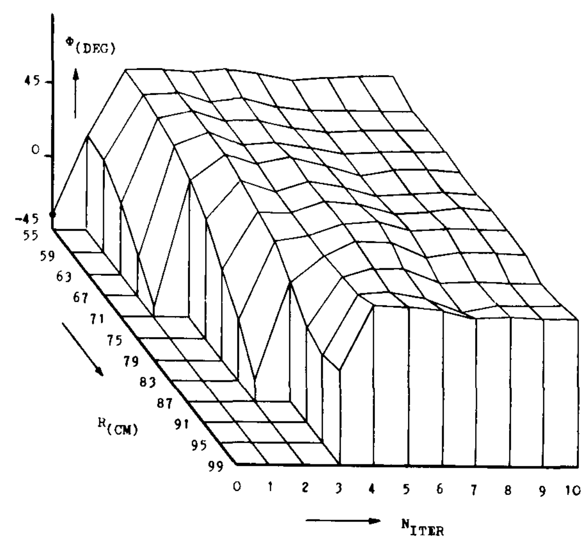

Fig. 5 Diagram of the leading and phase stabilization of the beam

third one the beam reached the final radius 99 cm. The dependence of the phase on the radius in the following iterations was close to the phase of maximum energy gain per turn (i.e. 45° for 90° Dee). The duration of one correction cycle is about 25 sec. The phase measurement in the mode of maximum accuracy takes 12 sec and the rest of the time is spend to calculate the current correction. The system has demonstrated a great reliability during a long period of testing in many modes of exploitation.

References

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3) V.N. Anosov et al. Preprint JINR P9-7339, 1973, 133.