ON A POSSIBLE REGIME OF ACCELERATION AND BEAM EXTRACTION IN AN ISOCHRONOUS CYCLOTRON

1969

SovietRxiv

Abstract

Full Text

UDC 539.107.6

PHYSICS

Yu. G. Basargin, R. N. Litunovskii

ON A POSSIBLE REGIME OF ACCELERATION AND BEAM EXTRACTION IN AN ISOCHRONOUS CYCLOTRON

(Presented by Academician B. P. Konstantinov, 9 XII 1968)

The present communication is devoted to the question of improving the monoenergeticity of a cyclotron beam. The authors of work ([1]) considered a calculated model of an isochronous cyclotron, in which it was proposed to proceed by carefully stabilizing all parameters of the accelerator. In this case the most difficult requirement is to maintain the specified tolerance on the constancy of the accelerating voltage. In addition, a small amplitude of radial oscillations is necessary, and to broaden the phase band a "trapezoidal" form of the half-wave of the accelerating voltage is required. On the other hand, as is shown below, there exists the possibility of using, in order to reduce the energy inhomogeneity of the beam, the analyzing properties of the magnetic field of the cyclotron upon extraction from a radius close to the boundary of radial stability (where the field inhomogeneity index $n \simeq 1$). For a synchrocyclotron such an extraction regime was considered in work ([2]) and was later successfully realized ([3]).

With an unstabilized accelerating voltage (but a well-stabilized magnetic field), the total energy inhomogeneity of the external beam will not exceed the magnitude of the energy gain per turn if, in the vicinity of the deflector, the successive turns corresponding to the greatest energy gain do not overlap. This is equivalent to the condition $2\rho \leq \Delta r_m$, where ρ is the amplitude of radial oscillations in the extraction zone, and Δr_m is the greatest separation of equilibrium orbits. The possibility of satisfying this condition for $n \simeq 1$ follows from the known formulas for Δr_m and ρ (for simplicity, the influence of the azimuthal variation of the magnetic field is not taken into account)

$$\Delta r_m \simeq \frac{r_k}{2(1-n)} \frac{\Delta W_m}{W_k}, \tag{1}$$

$$\rho = \rho_0/(1-n)^{1/4}. \tag{2}$$

Fig. 1. Cyclotron scheme: 1 –main dee; 2 –additional dee; 3 –source; 4 –shielding frame

Figure 1: Fig. 1. Cyclotron scheme: 1 –main dee; 2 –additional dee; 3 –source; 4 –shielding frame

Here r_k is the extraction radius; $W_k, \Delta W_m$ are the energy and the greatest energy gain at this radius; ρ_0 is the amplitude of radial oscillations in the central region, where $n \simeq 0$. For a given energy spread $\delta W/W = {}^1/_2 \Delta W_m/W_k$, the tolerance on ρ_0 follows from the relation

$$\delta W/W = 2(1-n)^{3/4}(\rho_0/r_k). \tag{3}$$

The practically realizable value $\rho_0 = 2$ mm gives $\delta W/W = 3 \cdot 10^{-4}$ for $r_k = 120$ cm and $n = 0.96$, which corresponds to $\Delta W_m/W_k = 6 \cdot 10^{-4}$. The main difficulty consists in ensuring a sufficiently small energy gain per turn in the cyclotron acceleration regime, where there is no phase stability.

In an isochronous cyclotron with an ordinary accelerating system $\Delta W = \Delta W_0 \cos\varphi$. At the end of acceleration one can create a sharp drop in the magnetic field (with small gaps in the "hills" of the magnetic system or by means of special windings) in order, without loss of intensity, to bring the beam to the region $n \simeq 1$. Then ΔW will decrease, since the phase band during acceleration in the nonisochronous regime shifts from the initial position in the vicinity of $\varphi = 0$, where its width is equal to $\Delta\varphi_i$, to the limiting position $\varphi = \pi/2$, where its width is $\Delta\varphi_k$. As follows from the equations of phase motion, $\Delta\varphi_k \simeq \sqrt[3]{2\Delta\varphi_i}$. If condition (3) is fulfilled, the energy spread

in the extracted beam will be $\delta W/W = (\sqrt{2}/2)(\Delta W_0/W_k)\sqrt{\Delta\varphi_i}$. The bunching effect leads to a very stringent tolerance on $\Delta\varphi_i$: for $\delta W/W = 3 \cdot 10^{-4}$, the required $\Delta\varphi_i = 2.5^\circ$, if $\Delta W_0/W_k = 2 \cdot 10^{-3}$. Narrowing of the initial phase band, while maintaining a small value of ρ_0, inevitably leads to a decrease in the beam current.

The noted limitation can be overcome if the doubled accelerating system shown in Fig. 1 is used in the cyclotron. The "main" dee, with voltage amplitude U_1, operates at a frequency close to the ion revolution frequency; a voltage with amplitude U_2 and triple frequency is applied to the second dee. The dees are connected in phase. For such a system the energy gain per revolution (excluding the first half-revolution) is

Fig. 1. Cyclotron scheme:
1 –main dee; 2 –additional dee; 3 –source; 4 –shielding frame

$$\Delta W(r,\varphi) = \Delta W_0(r)\,[\cos\varphi - a(r)\cos 3\varphi], \tag{4}$$

where $a(r)$ is a function defined as the ratio of the effective potentials on the dees; d is the gap width; r is the acceleration radius. For the system of Fig. 1, $a(r)$ reflects the transit-time effect of the accelerating gaps,

$$a(r) \simeq \frac{U_2}{U_1}\left[1 - \frac{1}{3}\left(\frac{d}{r}\right)^2\right], \tag{5}$$

In the general case $a(r)$ and $\Delta W_0(r)$ also depend on the angular extent of the dees and on the distribution of potentials along the accelerating gaps.

Injection takes place into the "main" dee, and during the first half-revolution the ions are not acted upon by the second dee. The initial phase band $\Delta\varphi_i$ lies in the vicinity of $\varphi = 0$ (Fig. 2a). In the first revolutions the factor $a(r)$ is appreciably less than unity even under the assumed condition $U_2 \simeq U_1$. Therefore the ion energy gain obtained in the first revolution proves sufficient to pass around the source. Thereafter isochronous acceleration is assumed, with the phase band $\Delta\varphi_i$ remaining fixed in the "well" on the curve $\Delta W(r, \varphi)$ (Fig. 2b). According to (4), (5), the depth of the well increases with increasing radius. After a certain number of revolutions, when $a(r) \simeq 0.9$, a positive perturbation is introduced into the isochronous dependence of the mean magnetic field $\overline{B}(r)$, shifting the phase band by about 55° into the region of the left maximum of the curve $\Delta W(r, \varphi)$ (Fig. 2c). In this case the width of the phase band decreases: $\Delta\varphi_s \simeq 0.2(\Delta\varphi_i)^3$*. When $\Delta\varphi_i < 1$, effective beam bunching takes place. The bunched beam is then accelerated again in the isochronous regime, but now with a large energy gain per revolution $\Delta W_{\max} \simeq 3eU_1$. At the end of acceleration a sharp decrease of the magnetic field is produced, shifting the phase band to the right–again into the well on the curve $\Delta W(r, \varphi)$. In accordance with the equations of phase motion, debunching of the beam occurs until the initial phase width is restored: $\Delta\varphi_k \simeq \Delta\varphi_i$ (Fig. 2d). Ions that have reached the region $n \simeq 1$ are extracted with a small energy gain per revolution. The resonance zones of betatron oscillations located in the region of the field decrease are crossed by the beam with a large energy gain per revolution. Therefore, if the corresponding tolerances on the irregular harmonics of the magnetic field and its gradient are met, the resonances appear less dangerous than in a synchrocyclotron of the same energy.

The energy spread in the extracted beam can be estimated as

* More precisely $\Delta\varphi_s \simeq 0.23(\Delta\varphi_i)^3 + \frac{2}{3}(1-a)\Delta\varphi_i$. Estimates of $\Delta\varphi$ are made on the basis of the consequence

$$\frac{\delta W}{W} \simeq \frac{eU_1}{W_k}(\Delta\varphi_i)^2$$

Fig. 2. Scheme of the phase motion: a —first half-turn; b —initial region; c —main acceleration stage; d —beam extraction stage

Figure 2: Fig. 2. Scheme of the phase motion: a —first half-turn; b —initial region; c —main acceleration stage; d —beam extraction stage

(it is assumed that (3) is satisfied, and at the end of acceleration $a(r) \simeq 1$). For $\delta W/W = 3 \cdot 10^{-4}$, with approximately the same number of ion turns as in the cyclotron example considered above with a conventional accelerating system, the permissible width of the starting phase band is quite reasonable from the standpoint of beam intensity: $\Delta\varphi_i = 37^\circ$ (and not 2.5°, as in the example mentioned). If the energy spread must be reduced by a factor p, then, all other conditions being equal, it is necessary to increase r_k by a factor p and to reduce $\Delta\varphi_i$ by a factor $\sqrt{p}$ (in the case of a cyclotron with a conventional accelerating system $\Delta\varphi_i$ is reduced by a factor p^2).

Fig. 2. Scheme of the phase motion: *a* —first half-turn; *b* —initial region; *c* —main acceleration stage; *d* —beam extraction stage

The voltage on the dees need only be stabilized to an accuracy of $3 \cdot 10^{-3}$; mutual phasing can be carried out with an accuracy of $2 \div 3^\circ$. No special requirements are imposed on the radial dependences of the perturbations of the isochronous magnetic field at the middle and final stages of acceleration: these perturbations may be selected empirically with the aid of correction coils.

The simplified scheme considered (Fig. 1) can be modified for use in modern ring isochronous cyclotrons with a magnetic system consisting of separate sectors. The phase band $\Delta\varphi_i$ is broadened by a factor of one and a half if the frequency of the additional accelerating system is the second (and not the third) harmonic relative to the fundamental frequency. It is important to note that, from the design standpoint, the described version of the cyclotron acceleration method is fully compatible with the concept of a "stabilized" cyclotron [1], where an additional accelerating system is also required, operating on the third (but, apparently preferably, on the second) harmonic.

Of independent interest is the effect of strong bunching of the beam during the transition from the trough to the maximum of the function $\Delta W(r, \varphi)$. If $\Delta\varphi_i = 37^\circ$, then $\Delta\varphi_{s\,\min} = 3^\circ$; if $\Delta\varphi_i = 20^\circ$, then $\Delta\varphi_{s\,\min} = 0.5^\circ$. Using an external debuncher, it is possible partially to compensate the energy nonmonochromaticity of the beam deflected from the radius of isochronous acceleration. In this case, in order to increase the difference in flight times, it is expedient to place between the cyclotron and the debuncher a special magnetic-optical system similar to that proposed in [4]. It also becomes possible simultaneously to increase the flux intensity and to reduce the duration of short neutron pulses obtained on a cyclotron by the method [5].

The authors express their gratitude to B. P. Konstantinov for proposing the research direction and for support.

Received
9 XI 1968

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Note: Figure translations are in progress. See original paper for figures.