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HIGH-EFFECTIVE BEAM EXTRACTION FOR RING CYCLOTRON OF HIGH INTENSITY

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Introduction. - The start-up and further development of cyclotron set-ups of the SIN [1] and TRIUMF [2] types indicate to the possibility of using circular cyclic accelerators in the region of mean currents of up to tens of mA at the energy of up to 1 GeV.

This possibility is based on the beam losses obtained already at the extraction and acceleration of the beam up to values approaching 10^{-3} (SIN) with a mean intensity of 100 μA.

The increase of proton beam mean intensities up to units and tens of milliamps is related to the necessity of losses further decrease, which is especially important at their local concentration in the region of the extracted beam, the power of which will be approaching several megawatts.

All the existing methods of beam extraction are based either on the mechanism of excitation of free (or forced) coherent oscillations near the closed orbits or on the mechanism of increasing the orbits separation in the zone of terminal acceleration radii.

The use of the first mechanism brings, inevitably, to noticeable beam losses due to the continuous spectrum of the particles' distribution on the emittance of the accelerated beam; the second mechanism necessitates, as a rule, a considerable increase in energy during one revolution in the zone of final acceleration radii [3].

The increase in the internal beam mean intensity of up to tens of mA brings to the increase of beam emittance until the values at which the desired increase of energy per one turn enters the domain of practically unattainable values. The joint application of orbit separation and excitation at the injection of coherent free oscillations in the extraction zone is effective, evidently, only at relatively low intensities corresponding to the narrow-enough spectrum of noncoherent oscillation frequencies [1].

The present report considers a possibility of avoiding this difficulty by means of using a special mechanism of equilibrium orbits expansion in the final radius zone of an accelerator with a periodic structure of the magnetic field [4].

1. The system of equilibrium orbits in the magnetic field periodic structure. - For the magnetic field of the type

$$H_z=\bar{H}(r)+\sum_{k=1}^{\infty} H_{kN} \cos\left[\beta_{kN}(r)-kN\phi\right] \qquad (1)$$

which is periodic in the plane of symmetry there exists periodic solutions (with the period $\frac{2\pi}{N}$) of the equation of motion for a discrete set of momenta p_i, which are defined by the relation $cp_i = eH(r_i)r_i\Lambda$ and are at a distance of

$$\Delta r = \alpha\frac{\Delta p}{p_i} r_i \qquad (2)$$

from each other along the average radius r.

Here $\alpha = \frac{p}{r_i}\left(\frac{dr}{dp}\right)_{r_i}$ is the equilibrium orbit momentum compaction factor (over the mean radius) and Λ is the dimensionless factor which depends only on the structure parameters of the field (1). Physically these solutions are identified with a set of equilibrium orbits which can be in the general case, both stable and unstable. This characteristic is also defined by the parameters of the field (1).

In case we limit ourselves to the terms which are proportional to $\frac{1}{N^2}$ the compaction factor for field (1) will be

$$\alpha = \left(1 + n + \frac{r}{\Lambda}\frac{d\Lambda}{dr}\right)^{-1} . \qquad (3)$$

The expression for Λ is defined from the equation of motion and for the harmonic 2 of the magnetic field it is defined, with an accuracy of up to $\frac{1}{N^2}$, from the equation

$$\Lambda^3-\Lambda^2-\frac{1}{2N^2}\left(\varepsilon_N s_N + \frac{1}{4}\varepsilon_{2N}s_{2N}\right)\Lambda - \frac{3}{4}\,\frac{\varepsilon_N^2+\frac{1}{4}\varepsilon_{2N}^2}{N^2} = 0 , \qquad (4)$$

where

$$n = \frac{r}{\bar{H}}\frac{d\bar{H}}{dr}, \quad \varepsilon_N = \frac{H_N}{\bar{H}}, \quad s_N = \frac{r}{\bar{H}}\frac{dH_N}{dr}.$$

For the first harmonic (N) it directly follows from (4) that

$$\frac{r}{\Lambda}\frac{d\Lambda}{dr} = \left[2N^2(3\Lambda^2 - 2\Lambda - \frac{\varepsilon s}{2N^2})\right]^{-1}\left[s^2 + \right.$$

$$\left. + \varepsilon d + \varepsilon s(1-2n) + \frac{3\varepsilon}{\Lambda}(s - \varepsilon n)\right], \qquad (5)$$

where

$$d = \frac{r^2}{\bar{H}}\frac{d^2H_N}{dr^2}.$$

If we leave in formula (5) only the terms (at $\Lambda \approx 1$) which make a certain contribution into quantity $\frac{r}{\Lambda}\frac{d\Lambda}{dr}$, then we can write with a several per cent accuracy the following

$$\alpha \approx \left[1 + n + \frac{1}{2N^2}(s^2 + \varepsilon d)\right]^{-1}. \qquad (6)$$

In the azimuth-symmetrical magnetic field $\alpha \approx \frac{1}{1+n}$, in a synchrotron with strong focusing $\alpha \approx 2(\frac{N}{s_N})^2$, in case there are no nonlinearities. The introduction of a square nonlinearity into the main harmonic of the field and namely the choice of the second derivation of the dependence $H_N(r)$ which should be negative for the expansion of the orbits, enables one to regulate within a wide interval the structure net of equilibrium orbits at a given value of momentum gain per revolution (Δ p) just through changing the function of variation distribution along the accelerator radius $H_N(r)$ in the extraction area.

For the choice of this function from (3) and (4) it is possible to receive a system of differential equations (by N, 2N):

$$\frac{d\Lambda}{dr} = \frac{\Lambda}{r\alpha}\left[1 - \alpha(1 + n)\right],$$

$$\frac{dH_N^2}{dr} + \frac{1}{4}\frac{dH_{2N}^2}{dr} = -\frac{3H_N^2}{r\Lambda} - \frac{3}{4}\frac{H_{2N}^2}{r\Lambda} + \qquad (7)$$

$$+ \frac{4N^2\bar{H}^2}{r}\Lambda(\Lambda - 1).$$

The numerical solution of this system at the introduction of the necessary dependence $\alpha(r)$ and at the given dependence of the mean field H(r), enables one to find the distribution factor of a variation harmonic selected for the creation of orbit expansion effect, and to define the dependence $\Lambda(r)$. From the analysis of system (7) it follows that in the final radii zone it is possible to increase five-tenfold the distance between two neighbouring closed orbits in comparison with isochronous motion zone at the values of $\frac{|d|}{2N^2} \approx (2 \div 2.5)$ which is practically attainable at $\varepsilon_N \approx 1$.

If the energy spread of the beam at the end of acceleration is less than the energy gain per turn (the mode of equal number of revolutions for all the particles), the process of equilibrium orbits expansion is equivalent to the corresponding five-tenfold increase of the accelerating voltage at the final radii.

The effective radial beam spread during the process of expansion can be evaluted from the expression:

$$\Delta r = \alpha r \frac{\Delta p_1}{p}, \qquad (8)$$

where Δp_1 is the momentum width of the beam in front of the expansion zone. Expression (8) is true under the condition $\frac{d\alpha}{dr} \approx 0$, i.e., at the constant factor α in the expansion zone, at the change of α the parameter αr in (8) is substituted by the mean value.

2. Stability of free oscillations. - The frequencies of free oscillations change considerably in the expansion zone. Thus, the frequency of Q oscillations somewhat exceeds the value calculated by the formula

$$Q_r^2 \approx 1 + n + \frac{1}{2N^2}(s^2 + \varepsilon d) + o(\frac{\varepsilon^2}{N^2}). \qquad (9)$$

The corresponding change of Q_z is estimated from the equation

$$Q_z^2 \approx -n + \frac{\varepsilon^2}{2} + \frac{\varepsilon^2 r^2}{N^2}(\frac{d\beta}{dr})^2 + \frac{1}{2N^2}(s^2 - \varepsilon d). \qquad (10)$$

From (9) and (10) it follows that on approaching the expansion zone the frequency of radial oscillations increases and the frequency of axial oscillations decreases; in the expansion zone the process is of the reverse character and $Q_r^2 > \frac{1}{\alpha}$ in all the cases.

Numerical investigations of stability in front of the expansion zone and inside of it confirm these results. Note, that at constant α in the expansion zone the transversal emittances of a beam are preserved and the change of natural frequency manifests itself in the effect of phase plane turn for a fixed azimuth.

3. Phase motion of the beam. - The isochronism of particles breaks in the expansion zone.

The value of the phase shift in this zone can be found from the expression

$$\Delta\varphi = 2\pi \sum_i \left[1 - \frac{1}{\alpha_i(1+n_i)}\right]\frac{\Delta r_i}{r_i}, \qquad (11)$$

where the summing (over i) corresponds to the number of turns in the expansion zone.

From (11) it follows that the phase shift in this zone

$$\Delta \phi < 2\pi \frac{\Delta r}{r} \quad , \qquad (12)$$

where Δr is the radial length of the zone.

Numerically, the value of the zone length does not exceed several per cent from the radius value, which indicates at an insignificant phase shift at the acceleration in this zone for low multiplicity of accelerating field.

The above-discussed results of forming the structure of equilibrium orbits in the isochronous cyclotrons can be used for preliminary selection of parameters at the realization of expansion effect. The detailed analysis is carried out, as a rule, by numerical methods, which take into account all the nonlinear terms defining a closed orbit.

The numerical calculation of the orbit expansion is given for the electron cyclotron with strong focusing [5] and for the meson factory SIN. Figure 1 presents the results for an electron cyclotron:

a) The dependence of average magnetic field and of the main variation harmonic in the expansion zone on the radius;

b) The orbits of particles for the last eight turns at the zero initial phase with respect to the acceleration field;

c) Radial emittances of a monoenergetic beam in the expansion zone for the azimuth cross section I.

Figure 2 presents a dependence of the radial spread of the electron cyclotron beam on the energy spread of the cross section I (figures near the straight lines show the number of the beam revolution).

Figure 3 gives the results of calculations for SIN:

a) the dependences of average magnetic field and main harmonic variation, the initial one (curve 1) and the one necessary for creating expanded orbits in the extraction zone (curve 2), on the radius;

b) beam radial emittances at the entrance into an electrostatic deflector.

Conclusion. - The considered method of separating the beam emittances at the final radii of cyclotrons with sectioned structure of the magnetic field opens new prospects for high-effective beam extraction from the acceleration chamber. This method, based on the separation of equilibrium orbits, is independent, within the wide limits, of extracted beam emittances; the changes of this beam in the expansion zone are limited to the cycling of the phase plane with respect to its own axis.

References

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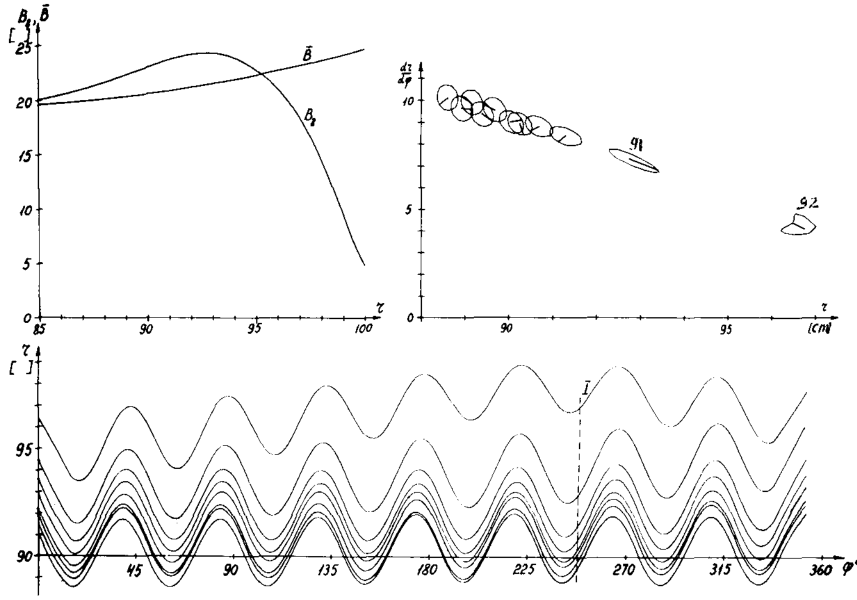

Fig. 1.

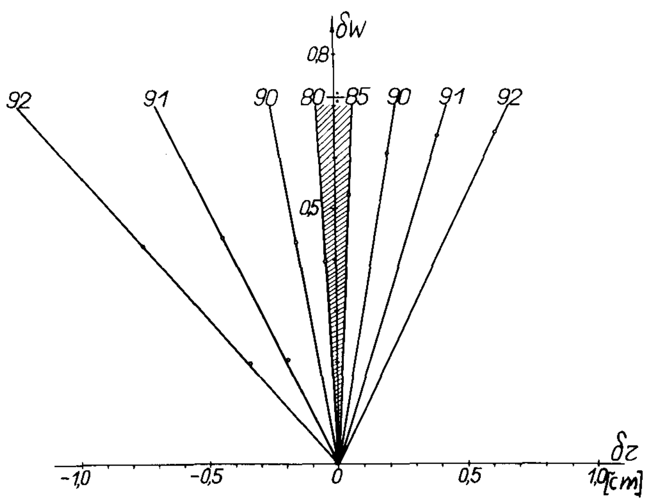

Fig. 2.

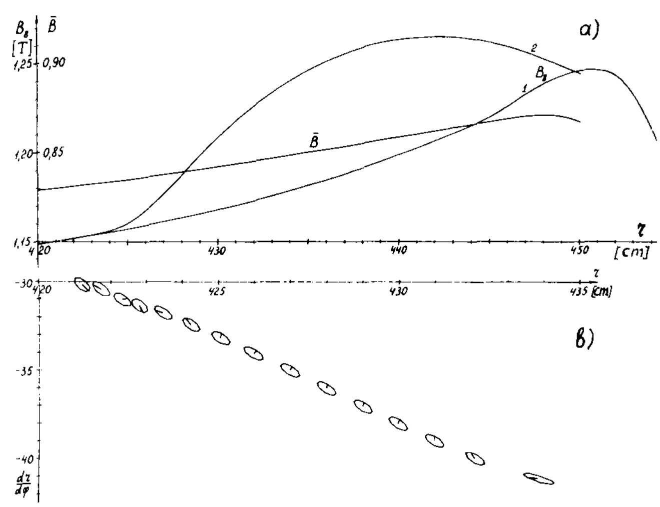

Fig. 3.