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A MONOENERGETIC CYCLOTRON

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A special sectioned isochronous cyclotron with external injection for acceleration of p, d, α, He^3, and Li^6 beams with a small energy spread (10^{-4}), a peak proton energy of 80 MeV, and an intensity of 100 μA is considered.

PROGRESS in research on the atomic nucleus during the last ten years was accompanied by an appreciable increase of the accuracy of the physical experiments, making it possible to discover new physical phenomena. This is connected, on the one hand, with the appearance of precision radiation detectors (for example germanium γ-quantum detectors), and on the other hand with the development of electrostatic tandem generators, which serve as the main tool for the study of the structure of the atomic nucleus. The largest of the existing installations make it possible to obtain beams of protons with energies up to 24 MeV at a relative energy spread $\Delta W/W \approx 10^{-4}$. Some laboratories will soon have accelerators consisting of two tandem generators, making it possible to accelerate protons to 36 MeV or somewhat higher, but with an appreciable decrease of the intensity of the accelerated beam.

At the same time, an analysis of the main trends in the development of research of the atomic nucleus shows that further appreciable increase of the energy and of the current of the accelerated particles is necessary, and at the same time the beam has to remain highly monoenergetic. It is not clear at present to what extent these tasks can be solved with the aid of tandem generators.

In the present paper we propose to use for these purposes a cyclic accelerator, namely a sector isochronous cyclotron, which has features that ensure the necessary monoenergetic character of the accelerated beam at high intensity. We shall call this accelerator a monoenergetic cyclotron.

Starting from the development prospects in the physics of the atomic nucleus in the coming decade, it is advantageous to choose the maximum energy of the protons in the 60–80 MeV range at beam intensities 100 μA, and to be able to control the energy relatively smoothly from 15–20 MeV to the maximum value.

Besides the protons, it is possible to accelerate with the monoenergetic cyclotron also deuterons, α particles, and $^3He^{+2}$ and $^6Li^{+3}$ ions. Such an accelerator is a multislit setup, which makes it possible to carry out extensive research on many of the latest trends in nuclear physics.

To obtain a highly monoenergetic accelerated beam ($\Delta W/W \approx 10^{-4}$) by cyclotron acceleration it is necessary to take measures to eliminate or to reduce greatly the effects that lead to the appearance of an energy spread in the accelerated beam. Foremost among these effects are the following: the energy inhomogeneity of the injector beam; the energy spread produced in the accelerated bunch of finite length as the result of the sinusoidal form of the accelerating voltage; the energy spectrum produced in the extracted beam when particles are simultaneously extracted from several orbits and the amplitude of the free radical oscillations exceeds the distance between the neighboring orbits.

In order to reduce to a minimum the energy spread during the injection, it is necessary to employ external injection of the beam into the cyclotron from an injector-accelerator, for example an electrostatic generator.

In order to reduce greatly the energy spread in the accelerated beam, it is necessary to decrease strongly the azimuthal dimension of the bunch, and also to smooth out the top of the accelerating-voltage wave. The former is ensured by choosing an appropriate time structure of the injector beam. The top of the wave of the accelerating voltage can be flattened by introducing a third harmonic of the accelerating voltage.

The decrease of the azimuthal dimension of the bunch leads to an increase of the particle density at a specified average intensity of the accelerated beam (100 μA), and to ensure spatial stability of the bunch it is necessary to make the frequency of the axial oscillations much larger than in the usual isochronous cyclotron. This can be done by increasing the depth of variation of the magnetic field.

The energy spread appearing during the course of the extraction of the beam can be eliminated in the proposed accelerator by increasing the radial separation of the orbits at the final radius and by decreasing the radial emittance of the injected beam, which also indicates the importance of using external injection.

An increase of the separation of the orbit is attained by decreasing the average magnetic field and increasing the increment of the bunch energy per revolution.

As will be shown later, to make the beam highly monoenergetic it is preferable to decrease the leading magnetic field, and consequently, to increase the radius of the orbit, rather than increase the energy increment per revolution. This decreases, by the same token, the value of $dW/dr \sim 1/r$, thereby facilitating the extraction of the monoenergetic beam from the cyclotron.

The foregoing considerations have caused us to choose as the basis an isochronous cyclotron with separated sectors, with a low magnetic-field induction, and with a relatively large radius of the final orbit.

Let us consider some specific features of the main systems of the proposed monoenergetic cyclotron.

Starting out from the premise that the accelerating system and the extraction system should be conveniently located, the magnetic system can be chosen in the form of four C-shaped sector electromagnets, each of which spans an angle of approximately 45°. To exclude the possibility of exciting radial oscillations by the accelerating system, and also for convenience in the extraction of the beam, we have chosen a magnetic-field structure in which the phase of the harmonics does not depend on the radius. In the median plane, such such a magnetic field is of the form

$$H_z = H(r)\left[1+\sum_{m=1}^{\infty}\varepsilon_m(r)\cos mN\varphi\right], \qquad (1)$$

where $H(r)$ is the average magnetic field corresponding to the isochronous character of the acceleration process; $\epsilon_m(r)$ are the harmonics of the magnetic field, which ensure axial stability of the accelerated particles; N is the number of sectors.

The assumed structure of the magnetic field excludes also the possible occurrence of internal nonlinear resonance in the central region of the cyclotron.

The average field increases with increasing radius in accordance with the requirement that the particle motion on the closed orbits be isochronous. The maximum growth of the average field with increasing radius corresponds to proton acceleration and amounts to 6–8%. When other particles are accelerated, this quantity decreases in proportion to $(Z/A)^2$, where Z and A are respectively the charge and mass of the ions. Adjustment of the dependence of the average field on the radius, necessitated when the apparatus is changed over to acceleration of other particles, is with the aid of a system of windings located on the surface of the pole pieces.

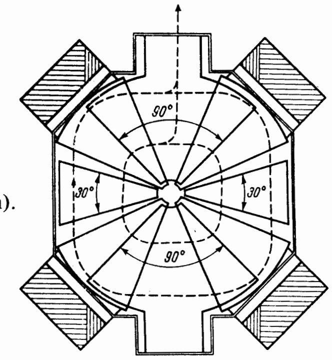

FIG. 1. Diagram of cyclotron (plan).

If one assumes a monoenergetic-cyclotron variant in which the energy of the accelerated deuterons amounts to half the proton energy, then the magnetic field in the central region remains constant for the entire set of accelerated particles. For other variants, it is necessary to change the overall level of the magnetic field.

To estimate the magnitudes of the typical magnetic fields of the monoenergetic cyclotron, we choose a variant corresponding to an energy increment of 200 keV per revolution and to an orbit separation of 0.44 cm at the final radius (W_f = 80 MeV). The average radius of the final orbit is then $\bar{r}_f$ = 400 cm and the average magnetic field at this radius is $\bar{H}_f$ = 3296 G. If we use as the injector an electrostatic accelerator with a potential 1.3 mV[1], then the average radius of the injection orbit will be 54 cm (Fig. 1).

The space-charge density corresponding to the average current in the accelerator, in the case of an elliptic cross section of the bunch, is determined from the expression[2]:

$$\varkappa = 8\bar{I}\,/\,ec\Delta_r\Delta_\varphi\Delta_z\beta, \qquad (2)$$

where Δ_r, Δ_φ, and Δ_z are the radial, azimuthal, and axial dimensions of the beam. To estimate the particle densities obtained in the case of a monoenergetic cyclotron, we assume the following values of the parameters needed for the calculation: $\bar{I}$ = 100 μA, Δ_r = 0.3 cm, Δ_φ = 0.25 rad (±6°), Δ_z = 1 cm, β_i = 0.0461 (W_i = 1 MeV). In this case κ = 0.5×10^8 cm^{-3}.

For nonrelativistic velocities ($\beta \ll 1$) the effect connected with the beam's own magnetic field is negligibly small and the space charge will cause only Coulomb spreading of the beam. The "transverse" effect leads to the following limitation of the frequency of the axial oscillations[2]:

$$Q_z^2 > 4\pi\frac{e^2}{E_0}r_\infty^2\varkappa\frac{\Delta_r}{\Delta_r+\Delta_z}, \qquad (3)$$

where $r_\infty = c/2\pi f_0 = r/\beta$ (r_∞ = 10.29 m and f_0 = 4.638 MHz).

For the parameters considered above, we obtain $Q_z > 0.5$, indicating that it is difficult to use ordinary cyclotrons in the case of small azimuthal dimensions of the beam, and that the orbits must be separated. The use of a sectionalized magnetic system with N = 4 and with the injection radius indicated above at

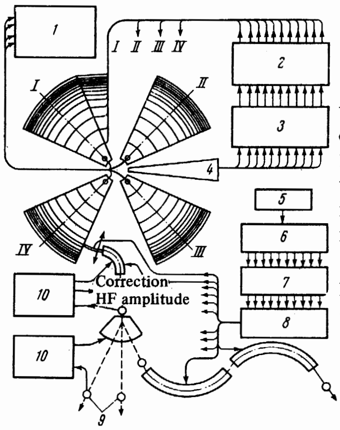

FIG. 2. Block diagram of control system for monoenergetic cyclotron: 1—nuclear field stabilizers, 2—regulated sources of supply for the correcting windings, 3—system for logical processing of the signals from the φ_n pickups, 4—φ_n pickups, 5—operator, 6—regime coder, 7—programmer-universal computer, 8—code-analog converter, 9—beam coordinate pickups, 10—analog correction system.

ever, by using the third harmonic of the high-frequency field and shifting its phase relative to the fundamental harmonic it is possible to compensate for the influence of the longitudinal field of the bunch[3].

The accelerating system of the monoenergetic cyclotron should ensure 200 keV per revolution and per change for all the accelerated particles (p, d, α, He^3, and Li^6). When changing over from the acceleration of one type of particle to the other, the frequency of the accelerating system changes in proportion to Z/A. To decrease the influence of the time of flight in the accelerating gap on the energy spread of the accelerated bunch, it is desirable to maintain the acceleration multiplicity minimal for all the accelerated particles. The bunch should acquire energy near the maximum of the accelerating voltage. To eliminate radial oscilla-

Basic parameters of monoenergetic cyclotron

Parameters	Accelerated particles				
	p	d	α	He^3	Li^6
Maximum energy W_f, MeV	80	60	120	120	180
Injector potential U_i, MV:					
Cockroft-Walton accelerator	0.780	0.628	0.628	0.618	0.628
Electrostatic accelerator	1.300	1.045	1.045	1.030	1.045
Intensity of extracted beam in terms of protons μA	100				
Energy scatter of extracted beam, ΔW/W	$1\cdot10^{-4}$				
Average value of magnetic field at final radius, G	3296	3985	3960	3460	3967
Average value of magnetic field in the central region, G	3037	3861	3837	3317	3844
Average radius of final orbit $\bar{r}_f$, cm	400				
Average radius of orbit at injection, $\bar{r}_i$, cm					
U_i = 0.6 MV	41.9				
U_i = 1.3 MV	54.0				
Radius corresponding to β = 1, r_∞, cm	1029.5	1619.6	1619.6	1413.9	1619.6
Magnitude of flutter of magnetic field	0.67—0.9				
Frequency of free oscillations:					
axial Q_z	0.8—0.9				
radial Q_r	1.10—1.17				
Frequency of revolution of accelerated particles, f_0, MHz	4.638	2.948	2.948	3.377	2.948
Multiplicity of acceleration, q	2				
Number of dees	2+2				
Amplitude of accelerating voltage on main dees, V_d, kV	50				
Aperture of dees, cm	4—5				
Distance between neighboring orbits on final radius Δr_f, cm	0.44	0.6	0.6	0.6	0.6
Range of smooth variation of energy of extracted beam	1 : 4				
Electromagnet supply power, kW	1500				
Lost power in HF system, kW	2·80				
Weight of magnetic system, tons	1200				

the minimum gap between the poles of the magnet equal to 16 cm, makes it possible to obtain for the axial oscillations frequency values Q_z = 0.8—0.9. The frequency of the radial oscillations changes during the course of acceleration the range $1.07 \leq Q_r \leq 1.15$.

At beam particle densities on the order of 10^8 cm^{-3}, an appreciable role can be played by effects connected with the longitudinal electric field of the bunch. In spite of the fact that the effect of "negative mass" cannot appear in isochronous cyclotrons ($d\omega/dE = 0$), the presence of the longitudinal field of the bunch can lead to an additional energy spread in the bunch. However,

tions produced by the influence of the transverse components of the electric field of the accelerating system the electric-field intensity vector should be directed along the closed orbits of the particles at all radii. Since the frequency of the radial oscillations is close to unity, the first harmonic should be missing from the Fourier series of the δ-function sequence identifying the process of the increase of particle energy during the revolution; otherwise, radial oscillations of considerable amplitude will appear, in the form of beats having the precession frequency. The second harmonic should be sufficiently small, otherwise beats with the large amplitude of the radial oscillations will also be produced as the result of the approach to the parametric-resonance band.

Starting from these considerations, the most suitable variant of the accelerating system is the ordinary cyclotron high-frequency system with a dee and a resonant line.

For the chosen four-element magnetic system, it is best to use as the main accelerating system two symmetrically placed 90-degree dees with edges of the axes of the magnetic sectors, and resonant lines connected to the centers of the gaps (see Fig. 1).

In this case, to ensure a maximum energy increment, the minimal frequency of the generator should be equal to double the frequency of revolution for all the accelerated particles. The resonant accelerating system can be tuned by movable panels at a constant length of the flat resonant line.

Smoothing of the top of the cosine wave of the accelerating voltage can be effected by introducing the third harmonic of the accelerating voltage. The accelerating voltage then takes the form

$$V = V_d (\cos \omega t - k \cos 3\omega t). \qquad (4)$$

If $k = 1/9$, then $V/V_d = 1 \pm 0.0001$ in a phase-variation range of approximately $\pm 10°$. The assumed phase span of the bunch is $\pm 6°$.

The third harmonic can be produced with the aid of additional accelerating electrodes, for example, as shown in Fig. 1. If voltage is applied directly from the main dee to the frequency tripler of the power supply of the additional electrode, then the phase instability of the main generator can be eliminated and the tripled parasitic phase shifts can be quite easily avoided. The required phase stability of the third-harmonic voltage is approximately 0.1°, which is close to the resolution of the modern standard phase meters.

The sector structure of the cyclotron and the sufficient separation of the orbits make it possible to use for the extraction system a deflecting device that moves radially and ensures a one-revolution extraction from the cyclotron chamber of the accelerated particles p, d, α, He^3, and Li^6 in the energy range $W_f - W_f/4$.

This device consists of an electrostatic deflector and a rotating magnet, which deflect the trajectory through 90° (see Fig. 1). The energy of the extracted beam changes discretely when the extraction system is moved to the next orbit, with suitable correction of the deflecting fields, and smoothly if the amplitude of the accelerating voltage is precisely varied. The electrostatic deflector and the rotating magnet are separated in azimuth by a distance approximately equal to one fourth of the wavelength of the radial oscillations.

The stringent requirements imposed on the monoenergetic character of the beam of the accelerated particles lead to rigorous tolerances with respect to the amplitude and frequency of the accelerating voltage and with respect to the magnetic field of the cyclotron. If the permissible deviation of the phase of the center of gravity of the bunch from $\varphi_n = 0$ is $\pm 1°$, the tolerance amounts to $\sim(1-3) \times 10^{-3}$%. Such a tolerance can be maintained only by using a system for automatically controlling the acceleration regime; this system acts on the amplitude of the accelerating voltage and on the magnetic field, using the results of measurements of the phase of the bunch and its radial position[4-6]. All the correcting winding, the accelerating-voltage amplitude regulator, the elements of the extraction unit, and the beam channels are automatically controlled by means of a system consisting of a discrete programmer for the operating regimes and analog-type correcting devices.

Taking into consideration the exceedingly wide spectrum of all the possible regimes, it is advisable to use as the programmer a small digital computer with magnetic memory, equipped with special input and output devices. The operation of all the control systems should be monitored from a control panel.

Figure 2 shows a block diagram of the control system of the monoenergetic cyclotron.

The table lists the main parameters of the apparatus.

The considered special isochronous cyclotron apparently provides an optimal solution of the posed problem. Naturally, individual elements of the apparatus may be modified during the development of the concrete design.

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