On the production of monochromatic beams using cyclotron acceleration

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ABSTRACT

Three methods of producing a cyclotron beam with low energy spread are considered. The first method is based on the known proposals for 'stabilised' separated-turn cyclotrons.[1,2] The second utilises the analysing properties of the cyclotron magnetic field when extracting the beam at a radius close to the boundary of radial stability.[3] In the third method monochromatisation of the external beam by a debuncher is considered.[4] The latter two methods require no high degree of stability of the accelerating voltage amplitude and phase.

1. 'STABILISED' CYCLOTRON

1.1. *Introduction*

In the 'stabilised' cyclotron, reduction of energy spread of the beam is obtained by stabilisation of the cyclotron parameters so that for all particles of the bunch the difference in the average energy increment per revolution does not exceed a given value $\delta W/W$. For widening the range of phases used a double accelerating system is utilised, and relations of voltage amplitude $a = U_g/U_o$ and their phasing are chosen so that the graph of the average energy increment per revolution $\Delta W = \Delta W_o (\cos \phi - a \cos q\, \phi)$ against phase has a flat top. The main technical difficulties are the high accuracy of stabilisation of the accelerating voltage, amplitude and phase ($\delta U/U \approx 3 \times 10^{-5}$ and $\delta\phi < 0{\cdot}1°$ at $\delta W/W = 2 \times 10^{-4}$) and the problem of maintaining the acceleration isochronism in the given range ($\Delta\phi < 2°$). The requirement for spatial separation of orbits limits the amplitude of radial oscillations, $\rho <$ 2 to 3 mm.

By means of computer calculations a detailed analysis was made of the orbit properties of a ring cyclotron with four separated sectors (45°), accelerating protons from 1 to 80 MeV with an exit radius of 300 cm and 320 keV energy gain per revolution (phase band width 10°). Three versions of the accelerating system with supplementary dees were considered (Fig. 1). A preliminary analysis

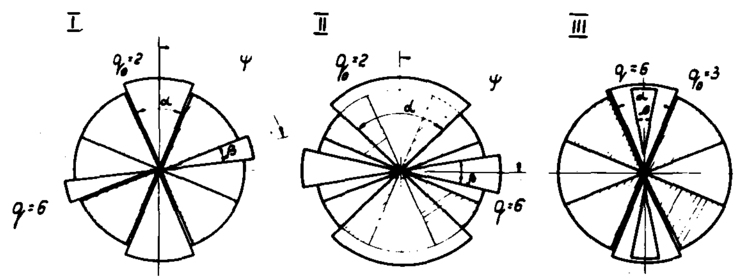

Fig. 1. Schemes for accelerating systems in isochronous cyclotrons, intended to give beams with small energy spread

of the orbits in the ring cyclotron without a supplementary accelerating system was carried out.

1.2. *Results of calculations*

It appeared that for all configurations considered it was possible to obtain orbit separation throughout the whole acceleration by selecting the injection conditions, the particle corresponding to the beam centre moving over a certain 'axial' trajectory. The crossing of accelerating gaps by the particles does not lead to additional modulation of the beam envelope, even when the radial oscillation frequency is very near to unity. Perturbations of the second harmonic type, introduced by the accelerating system, produce changes inversely proportional to the square of the radius. From orbit theory[5] it follows that in this case the resonance $\nu_r = 2/2$ is not excited.

The mode of acceleration considered leads to additional energy spread, which depends on the accelerating system geometry. The longitudinal characteristics of the beam were calculated as functions of revolution number, effective angular length of the main and supplementary dees, phase shift between the dees, energy gain per revolution, and bunch energy. The bunches have longitudinal extent $\phi = \pm 5°$. A preliminary analysis was made of the orbit parameters in a cyclotron with two 45° dees, placed in opposite valleys and operating on the second harmonic. For the particle with zero starting phase moving over an axial trajectory, the characteristics change smoothly at the beginning of acceleration and thereafter remain constant. For the particle with $\phi = 0°$, but starting with an initial displacement from the axial trajectory, the longitudinal characteristics are periodic in nature. This is the consequence of the common condition that vectors of phase space ($\delta\phi = \phi - \phi_{ref}$, $\delta W = W - W_{ref}$) correspond to the projection of a four-dimensional ellipsoid of particle distribution over co-ordinate axes $\delta\phi$ and δW. For the particle with starting rf phase $\phi \neq 0°$ the conditions of motion are quite different. Therefore its own axial trajectory exists for this particle. The presence of a constant component in the longitudinal characteristics of the orbits is explained on one hand, by the presence of the second harmonic component of the orbit relative to the axial trajectory of the particle with $\phi = 0°$, and on the other hand, by the time difference of the motion for particles with ϕ varying during their passage through the dee.

In addition, three versions of a ring cyclotron with supplementary dees were considered:

(a) A system, consisting of two 45° main dees and two 15° supplementary dees, placed as shown in Fig. 1. The main and supplementary dees operate on second and sixth harmonic respectively.

(b) A system consisting of two 90° main dees and two 30° supplementary dees (operating on second and sixth harmonics).[2]

(c) A system consisting of two 45° main dees and two 22° 30′ supplementary dees, placed symmetrically inside the main ones (operating on third and sixth harmonics).

The calculation showed (Fig. 2) that additional energy spread (introduced by the accelerating system due to the discreteness of acceleration) for a proton

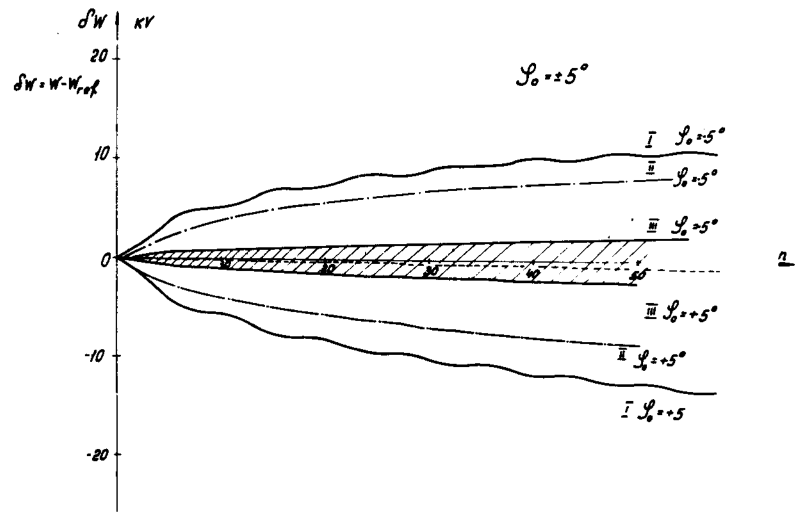

Fig. 2. Energy spread δW (n) *for different versions of accelerating systems in ring cyclotrons*

beam with an energy of 80 MeV was ±20 keV in the first version, ±13·6 keV in the second version, and ±3·5 keV in the third. The supplementary energy inhomogeneity of the beam is caused by the presence of factors linearly-dependent on rf phase, the constant component of effective angular length of the dees, and also by system de-phasing. The latter appears as a result of the difference between the actual trajectories of particles and their equilibrium orbits.

For particles with different starting phases compensation of path difference through each semi-revolution takes place. Therefore dephasing is a minimum on azimuths $\theta = m\pi$ (measured from the axis of the main accelerating system). This is why, to decrease energy spread, it is necessary to place supplementary dees inside the main ones. Energy spread can be decreased to ±12 keV, ±7 keV, and ±2 keV for the first, second, and third versions by tuning the phase shift between the accelerating systems. At an injection energy equal to 4 MeV energy spread is decreased to ±6 keV for a cyclotron with the first type of acceleration system.

So the possibility of using accelerating systems, placed in the field-free sectors in 'stabilised' cyclotrons has been confirmed.

2. BEAM EXTRACTION AT $n \approx 1$, IN CYCLOTRONS WITH DOUBLE ACCELERATING SYSTEMS[3]

With an unstabilised accelerating voltage (but with well stabilised magnetic field) the total energy inhomogeneity of the external beam does not exceed the maximum value of the energy increment per revolution ΔW_m, if the turns near the deflector, corresponding to ΔW_m, do not overlap. At given energy spread $\delta W/W_k = \pm\frac{1}{2}\,\Delta W_m/W_k$, (subscript k refers to the last turn), the tolerance on the initial amplitude of radial oscillations ρ_o is derived from the dependence

$$\frac{\delta W}{W_k} = 2(1-n)^{3/4}\frac{\rho_o}{r_k}$$

This dependence shows that, approaching the boundary of radial stability, $n = 1$, separation of orbits Δr_m increases faster than the amplitude of radial oscillations ρ.

The main difficulty is in obtaining sufficiently small energy increments in the cyclotron mode of acceleration. Such a mode of beam extraction was proposed for the synchrocyclotron,[6] and later successfully accomplished.[7] Small energy increments in the beam extraction region may be obtained in the case where the double accelerating system (Fig. 3) is used in the cyclotron. The 'main' dee with

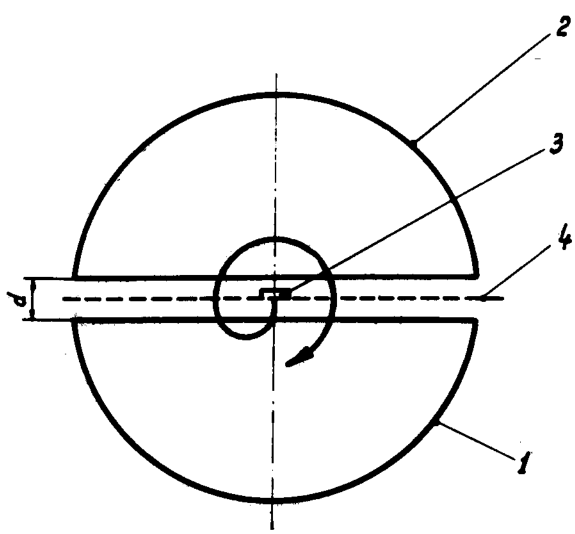

Fig. 3. Simplified scheme for a cyclotron: (1) Main dee; (2) Supplementary dee; (3) Source; (4) Screening frame

an amplitude U_o operates at a frequency near to that of the ions; the voltage U_q ($q = 3$) is applied to the second dee. Relations of amplitude $a(r) = U_q/U_o$ are chosen to be about unity. In the general case $a(r)$ and $\Delta W_o(r)$ depend on the angular extension of the dees and the efficiencies of the accelerating gaps.

Particles are injected into the 'main' dee. The initial range of phases is supposed to be in the vicinity of $\phi = 0$ [Fig. 4(a)]. During the first revolutions $a(r)$ is considerably less than unity even with the assumption of $U_q = U_o$, and therefore the energy increment is sufficiently large to enable particles to pass around the source. Further, isochronous acceleration is supposed, and the phase range $\Delta\phi_i$ remains fixed in the well of the curve $\Delta W(r, \phi)$ [Fig. 4(b)], and here the well depth increases with increasing radius. After several isochronous revolutions positive (or negative) perturbation takes place, which shifts the phase range by ~55° to the region of the left (or right) maximum of the curve of $\Delta W(r, \phi)$ [Fig. 4(c)]. At $\Delta W_o(r)$, $a(r)$ = const, the shaded area of the phase range in Fig. 4 is invariant, so its width in the maximum region is

$$\Delta\phi_s \simeq 0{\cdot}23\, \Delta\phi_i^3 + \tfrac{2}{3}\,(1 - a)\Delta\phi_i$$

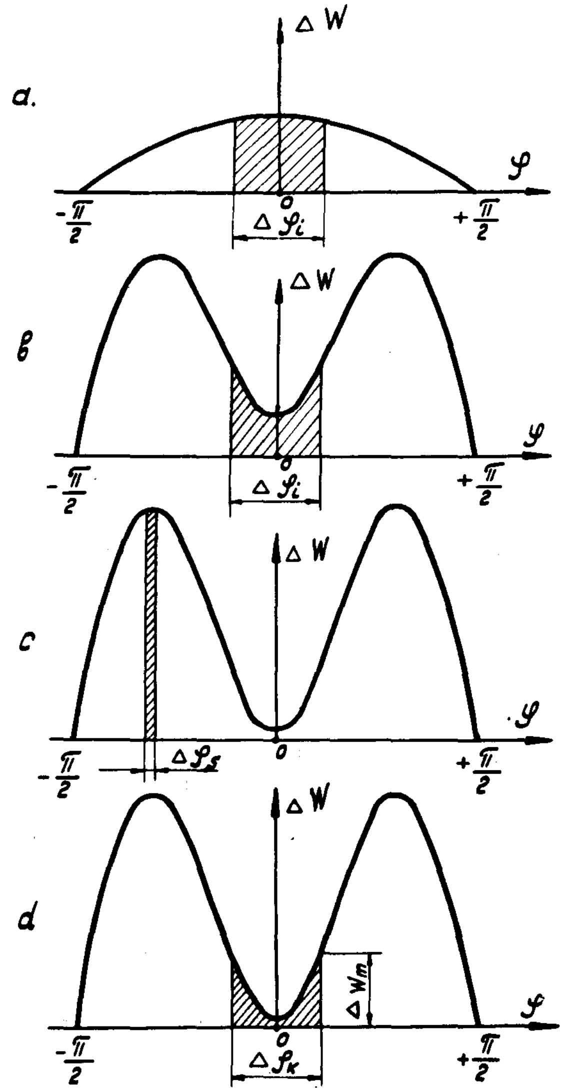

Fig. 4. Scheme of phase motion: (a) First half-revolution; (b) Initial region; (c) Main stage of acceleration; (d) Stage of beam extraction

When $\Delta\phi_i < 1$ effective bunching takes place; the bunched beam is accelerated again in the isochronous mode, but with large energy increments per revolution $\Delta W_{max} \approx 3eU_o$. At the end of acceleration a sharp fall-off of magnetic field can be produced (with small gaps in the 'hills' or with the help of special windings), which shifts the phase range to the right (or left) again into the well of the curve $\Delta W(r, \phi)$ [Fig. 4(d)]. Debunching of the beam takes place until the initial phase width is recovered and ions reaching the region $n \approx 1$, are extracted with small energy increments per revolution. Resonance zones of betatron oscillations in the region of the field fall-off are crossed with large energy increment per revolution.

For an energy inhomogeneity of the external beam of $\pm 3 \times 10^{-4}$, the tolerable width of the starting phase range is $\Delta\phi_i \approx 37°$. In this case $\Delta W_o/W_k = 1{\cdot}5 \times 10^{-3}$, $r_k = 120$ cm, $\rho_o = 2$ mm and $n = 0{\cdot}96$. In order to decrease the energy spread by a factor of m, it is necessary to increase the radius by a factor of m and to decrease $\Delta\phi_i$ by a factor of $\sqrt{m}$.

The simplified scheme of Fig. 3 can be modified for application in isochronous ring cyclotrons with a magnet system consisting of separate sectors. It is preferable to have a supplementary accelerating system, operating on the second harmonic (in this case, from the point of view of design there is complete consistency with the scheme for a 'stabilised' cyclotron). Tolerances on stabilisation of phase and amplitude of accelerating voltages are about 1° and 10^{-3}, respectively.

The effect of beam bunching in the intermediate stage of acceleration can be used to obtain sub-nanosecond pulses of fast neutrons, as well as to enable monochromatisation of the extracted beam to be achieved with the help of an external debuncher. In addition, bunching effects could be used in small cyclotrons intended for particle injection into large ring cyclotrons.

3. EXTERNAL BEAM MONOCHROMATISATION

The two previous methods for obtaining monochromatic beams in isochronous cyclotrons require a large extraction radius, which is more conveniently obtained in new machines with separated sectors. However, it is possible to monochromatise the beam extracted from 'conventional' cyclotrons with the help of an external debuncher. In the case of a cyclotron, direct application of a debuncher is rather difficult, because the required momentum separation of particles is only attained with a flight path of several hundred metres. In order to decrease the flight path an achromatic bending system, located between the cyclotron and the debuncher is used.[4] This system is similar to that proposed for the monochromatisation of the beam of an electron linac.[8] At this conference a report[9] describing a particular version of a monochromatisation system for cyclotron beams is presented.[9]

The problem of monochromatisation of the external beam to $\pm 2 \times 10^{-4}$ (with initial energy inhomogeneity $\pm 2 \times 10^{-3}$), seems to be solvable, if the phase width of bunches in the cyclotron does not exceed 5°. It should be noted that after the debuncher the phase width of the monochromatised beam will be 85°, which is a factor of two larger than the phase width attained in 'conventional' isochronous cyclotrons and a factor of six larger than in the 'stabilised' cyclotron.

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