THE ASPECTS OF OPTIMIZATION OF BEAM ACCELERATION AND EXTRACTION CONDITIONS IN CYCLOTRON WITH EXTERNAL "ACTIVE" MONOCHROMATIZATION SYSTEM

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ABSTRACT

The results of the investigation of optimization of acceleration condition and beam extraction in the 200÷300 MeV ring cyclotron, operating together with external active monochromatization system are reported. It is shown, that it is possible to obtain the beam with current of some tens of microamper with transverse emittance 3π mm.mrad at energy inhomogeneity 2.10^{-4} and duty factor 0.2.

INTRODUCTION

At Oxford Conference the paper[1] describing the external beam monochromatization system of the A.F.V. cyclotron with R.F. cavity (debuncher)field was presented. The longitudinal momentum separation of the particles, required in this case is carried out in achromatic bending system. Recently, the successful operation of similar scheme of beam monochromatization of the electron linear accelerator was reported [2].

The system of cyclotron beam monochromatization not only compensates energy spread, but also increases bunch duration and controls smoothly the beam energy in small range[1]. In the present work the problem of beam acceleration and extraction modes optimum from the point of view of monochromatization system application in cyclotron is qualitively considered. This is a ring cyclotron with external injection (of Indiana type[3]) with proton energy up to 200-300 MeV, though the conclusions are valid for "conventional" A.F.V. cyclotron. Acceleration on the 6-th harmonic allows to carry out the monochromatization system of this cyclotron more compact, than in the case of 100 MeV cyclotron considered earlier[1].

In principle, an other method than in[1] of energy inhomogeneity compensation by R.F. field is possible, when longitudinal component of electric field in the cavity is proportional to the distance from its axis. The cavity is preceded by bending system creating large transverse momentum dispersion[4]. The transverse emittance of the monochromatized beam is increased for the beam with zero phase length by the same factor that the energy spread is reduced; also there is an effect of additional emittance increasing, when bunch duration is different from zero one. After beam monochromator of SLAC electron accelerator the computed transverse emittance is increased by 135 times[4]. It is clear that in the case of cyclotron this is unpractical.

1. ACCELERATION MODES AND DUTY FACTOR

For successful functioning of monochromatization system the beam with narrow phase band should be accelerated in cyclotron[1]. At narrow phase band $\Delta\varphi$ the single-turn extraction mode was considered natural, when at the process of isochronous acceleration the bunch phase is "frozen" at the top of the accelerating halfwave[5]. But instability of accelerating voltage gives instability of average beam energy (within energy gain per turn ΔE_a), though instant energy spread ΔE_i is small. In fig.1a the longitudinal beam emittance after deflector and the range of its shifting on phase plane($\Delta E,\varphi$) is plotted roughly for this case. Beside it is the same after debuncher. It is considered, that for the experiments the beam with energy spread ΔE_m is used. It is seen, that the length of the used portion of the bunch is even decreased and the longitudinal bunch position is unstable. Thus at single-turn extraction mode the function of monochromatization system is the compensation of accelerating voltage instability without improving duty factor.

If at acceleration the narrow phase band is sufficiently shifted relative to the top of accelerating voltage, then the particles with different number of turns get into the deflector. For example, if phase band of 6° width is shifted by 20°, then extraction is carried out within 10 turns at total number of turns equal to 250. Beam properties at such multiturn mode of extraction are well commented in the work[6]. In this case energy spread is about energy gain per turn at stable average energy. The longitudinal space charge effect can be useful. In fact, 100% extraction efficiency is not achieved but 80-90% efficiency is practically possible.

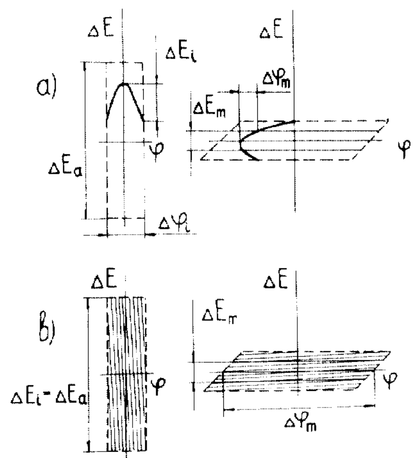

Fig.1. Longitudinal emittance at cyclotron exit and after debuncher:
a - single-turn extraction mode;
b - multiturn extraction mode;
ΔE_i, $\Delta\varphi_i$ - initial energy spread and phase width; ΔE_a - energy gain per turn; ΔE_m, $\Delta\varphi_m$ - energy spread and phase width of the used portion of monochromatized beam.

Fig.1b illustrates the transformation of longitudinal emittance for the second mode. After the deflector the particles fill completely the rectangle on the phase plane (ΔE, φ). Stripped emittance structure is connected with multiturn extraction [6]. After debuncher the bunch is stretched over maximum value, defined by monochromatizalion system parameters. It is seen from fig.1b, that at multiturn extraction mode duty factor is slightly depends on energy spread ΔE_m of the used portion of monochromatized beam.

If the beam injected in a ring cyclotron is bunched by an external buncher, then after the inflector the beam has energy spread comparable with energy gain per turn. At such a mode duty factor after debuncher slightly depends on phase band position.

Recently a practical method of matching particle acceleration modes in conventional A.F.V.injector cyclotron and ring cyclotron was offered, when frequencies of accelerating systems differ by noninteger factor[7]. In this case at using monochromatization system the optimum duty factor will be, when narrow phase band is shifted at acceleration relative to the top of sinusoid just more than in the example considered above.

2. HARMONIC NUMBER

Magnitooptic part of monochromatization system is more compact at the higher number of accelerating voltage harmonic. The effective length of the system[1], required for longitudinal momentum separation, is proportional to extraction radius divided by the harmonic number. The design of separated-sector ring cyclotrons[3] allows to use the accelerating system, operating at much higher frequencies than in conventional cyclotrons.

3. AN EXAMPLE OF A PARTICULAR SCHEME

In fig.2 a ring cyclotron with outer beam radius about 300 cm is shown, which is similar to Indiana cyclotron[3]. Acceleration is supposed atthe 6-th harmonic. Magnetic optics of monochromatization system consists of two 135^0 magnets, one 270^0 magnet and two quadrupoles[8]. Bending magnet field is inhomogeneous (n=0.832), bending radius is equal to 200 cm. The initial dispersion is created by the magnet M_1, the lens Q_1 "drive" disperse trajectories, the longitudinal momentum separation is created at the expense of trajectory length difference in the magnet M. Then the beam is symmetrized by the lens Q_2 and the magnet M_2. For the particles having momentum difference $\pm 10^{-3}$ the longitudinal separation is ±42 cm, which corresponds to $\pm 48^0$. The debuncher T_2 operates at frequency of cyclotron accelerating system. The cavity T_1 is intended for energy variation in small range.

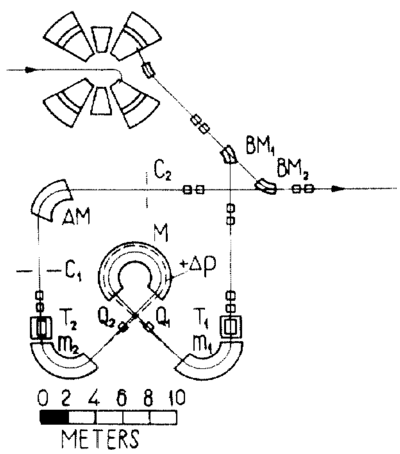

Fig.2. Possible scheme of beam monochromatization of ring cyclotron.

Analyzing magnet AM controls the energy of monochromatized beam.

The scheme of fig.2 should involve sextupole lenses, compensating the aberrations of transverse and longitudinal motion.

4. MONOCHROMATIZATION SYSTEM EFFICIENCY

The particle portion extracted from cyclotron with energy spread $\Delta E_m/E = 2.10^{-4}$ after analyzing slit C2 (fig.2) at different phase width of the beam accelerated in the cyclotron has been calculated. It is assumed that at cyclotron exit energy spread is equal to 4.10^{-3}. Initial distribution of energy intensity is assumed according to the cosine square law; phase distribution is assumed to be triangular. All these data refer to the full width at half-maximum of distribution curves. The sinusoidal form of debuncher R.F. voltage is taken into account.

In fig.3 the curve 1 corresponds to dependence of system efficiency on phase width of accelerated beam at fine system adjustment. It is seen, that at initial phase width of 6^0 58% of the beam extracted from cyclotron have energy spread within 2.10^{-4}, phase bunch length being 72^0, if multiturn extraction mode is used.

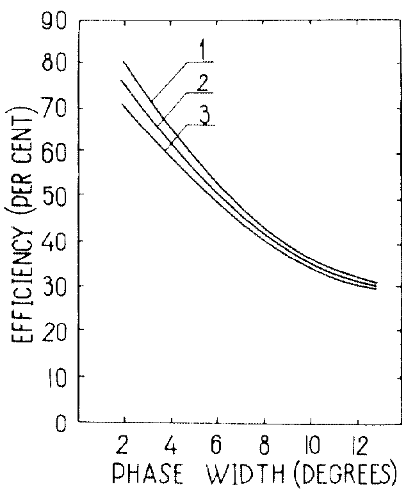

Fig.3
Percent of monochromatized beam particles with energy spread within 2.10^{-4} (efficiency of monochromatization system).

5. TRANSVERSE EMITTANCE

Achromatic magnetooptic system does not change the value of transverse emittance. Horizontal emittance of nonmonoenergetic beam is increased due to transverse dispersion at extraction from cyclotron. This effect can be compensated by the bending magnet placed between cyclotron and monochromatization system. In fig.3 achromatization of extracted beam is carried out by the magnet BM_1 and optic elements preceding it. Beam emittance after BM_2 is equal to the emittance of the beam circulating in cyclotron. If the amplitude of radial and axial oscillations is about 3 mm, then the appropriate transverse emittance is equal to 3π mm.mrad.

If the beam injected in the ring cyclotron has energy spread due to external buncher, then with a view to prevent the growth of radial oscillation amplitude it is necessary to arrange the ion optics elements after the buncher which provide getting of the particles with different energies on respective orbits. The similar problem is solved at injection into synchrotron (see, for example[2]).

6. TOLERANCES

Non-close tolerances of accelerating voltage amplitude and accuracy of isochronous field forming by trimming coils in cyclotron are assumed, if multiturn extraction mode is used [6]. In fig.3 the curve 3 corresponds to phase shifting of the debuncher (or the beam bunch) by 1^o. It is seen that this decreases the system efficiency by 5-8%.

The curve 2 of the same fig. corresponds to 3% deflection from optimum voltage value at the drift tube of the debuncher, It is seen that accuracy of voltage adjustment is non-critical.

Magnetic field stability tolerance of the magnets in monochromatization system is 2.10^{-5}, tolerance for quadrupole lenses is 10^{-4}.

Tolerance for stability of phase band position of the beam extracted from cyclotron is most critical. At 250 turns and the sixth harmonic the accelerated phase is shifted by 1^o at instability of magnetic field level of cyclotron 2.10^{-6}. The application of pulsation suppression schemes allows to decrease rapid changes of the field below this level. The effect of slow changes of the field can be compensated by automatic tuning system of bunch phase position with using pick-up electrodes. In this case stability of cyclotron magnetic field at the level of 10^{-5} is sufficient.

7. CONCLUSION

The possibility of obtaining 200-300 MeV beam with the current of some tens microamper and transverse emittance 3π mm.mrad at energy spread 2.10^{-4} and duty factor equal to 0.2 from ring cyclotron with external monochromatization system may be considered valid. Also, the requirements beyond the limits of nowadays possibilities are not claimed to the cyclotron. It is important, that multiturn extraction mode promotes at the same time to increasing of duty factor and tolerance weakening.

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