ON THE HIGH EFFICIENCY EXTRACTION (~ 100%) FROM THE SECTOR CYCLOTRON

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This paper examines possible variants of the beam particle extraction from the sector cyclotron with an efficiency near 100%. Requirements for tolerances and stability of the magnetic and accelerating high frequency fields of the cyclotron are presented. The necessity of the flat-top acceleration regime is proved. It is concluded that the use of the closed orbit expansion effect for the beam extraction from the sector cyclotron has advantages in what concerns the increase in the efficiency of the set-up as a whole.

1. Introduction

Increasingly active research on the high-intensity accelerators in connection with C.Rubbia's proposal about the energy amplifier for inexhaustible nuclear energy production [1] requires a substantiated answer to the question of whether linear or cyclic accelerators should be used for this purpose. The evident advantages of the sector cyclotron over the linac in the range up to 1 Gev with accelerating currents 10 mA are constantly doubted due to its only draw back, namely seemingly difficult or completely impossible highly efficient beam extraction from the cyclotron. However, the available data on this problem confirmed by already performed, tentatively examined, or newly proposed methods point to feasibility of the extraction system with efficiency close to 100%.

Let us briefly review the current achievements in high efficiency extraction from sector cyclotron. Coming first is the evident success of the accelerator complex PSI, where the extraction coefficient is 99.97-99.98 at the adequate tuning of accelerator system [2]. This extraction from the PSI sector cyclotron was carried out using the precession mechanism with fully frosen last orbits at the extraction stage and the voltage for each of the four main accelerating resonators being 730 kV.

At JINR (Dubna) the closed orbit expansion effect discovered in 1972, have been theoretically and experimentally investigated for several years [3]. Forming the magnetic field variation drop in extraction region, one may increase the radial gain per turn of successive orbits, which under the same conditions of frozen last orbit guarantees 100% extraction coefficient at smaller energy gain [4].

The results of the computer calculations for the beam particle extraction from the super-cyclotron using the closed orbit expansion effect are shown in Fig. 1, [5].

Finally, recall Y. Jongen's proposal at the 14th Cyclotron Conference about the so-called "Auto-Extraction System" using the drop of the magnetic field at its periphery and the specially introduced first harmonic of the magnetic field.

All above-mentioned beam particle extraction methods involved severe requirements to the tolerance and stability of the last orbits before extraction, which in turn, defines the tolerance for the formation of the stationary magnetic field of the cyclotron and for long-time stability of the accelerating high-frequency field, consequently leads to the frozen orbits regime.

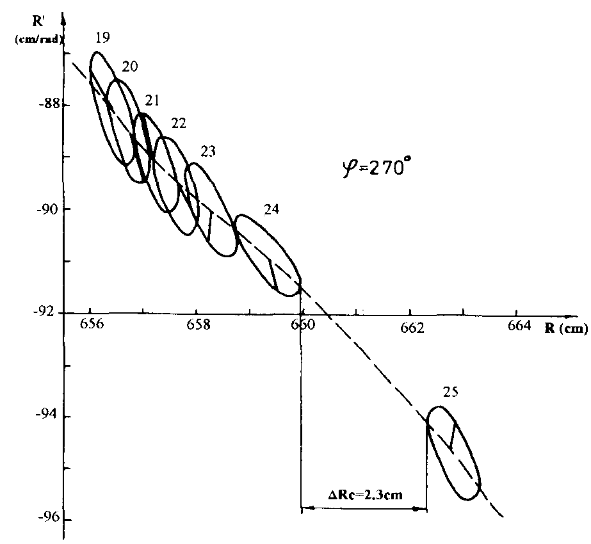

Figure 1: Results of the computer calculation beam particle extraction from the supercyclotron.

In spite of different points of view on the high efficiency of beam particle extraction from the sector cyclotron, attention should be paid to some similarity in their realization, which is determined by the real conditions, arising on the peripheral magnet of the cyclotron, actually on peripheral magnet, where conditions for beam particle extraction are formed, we have a spontaneous drop of the average magnetic field and a drop of its main harmonic.

Recall that the turn separation due to the energy gain may be expressed as

$$\Delta r = \alpha r \frac{\Delta E}{\beta^2 E}, \quad (1)$$

where r is the instantaneous radius, ΔE is the energy gain per turn, E is the total energy of accelerated particles, $\beta = v/c$; α is equilibrium orbit momentum compaction factor, which is related to the average radius R of the orbit and to the parameters of the magnetic field by the equation [4]

$$\alpha = \frac{dr}{dp}\frac{p}{r} \simeq$$

$$\simeq \left[1 + n + \frac{B^2 N}{2N^2 \bar{B}^2}(n_N^2 + \frac{r^2}{B_N}\frac{d^2 B_N}{dr^2})\right]^{-1}, \quad (2)$$

where p is the momentum of accelerated particles, $n = \frac{d\bar{B}}{dr}\frac{r}{\bar{B}}$ is the field index, $\bar{B}$ is the average isochronous field, $n_N = \frac{dB_N}{dr}\frac{r}{B_N}$, B_N is the amplitude of the main field harmonic, N is the period number. From equation (2) for the momentum compaction factor we have several variants of changing α. This can be done by changing the main harmonic amplitude or its first and second derivatives, by changing the average magnetic or the field index, and by changing their combination. Appropriately changing and forming the above parameters of the magnetic field in each concrete case one may obtain a desirable increase radial gain in the extraction region.

It is also necessary to mention the following, since in the case under consideration the particle beam is extracted into a region where the radial oscillation frequency Q_r approaches 2 and $Q_r \sim \gamma$, $\gamma = E/E_0$ passages through all possible resonances, including coupling resonance of radial and vertical oscillations, must be numerically calculated.

2. Tolerances and flat-top regime

Now let us consider tolerances. The tolerance for the average magnetic field is defined by the allowed phase shift for the beam phase motion during the acceleration and depends on the energy gain per turn. At $eU_{ac} = 2$MeV it is in the range $\Delta\bar{B}/\bar{B} = (2 \div 0.8) \times 10^{-4}$. Less severe requirements are imposed on tolerances for the amplitude of the lowest harmonic which must not exceed $\Delta B_N/B = 10^{-3}$ in the extraction region. The tolerance for the difference of the accelerating field frequency to under the same conditions must not be greater than $\Delta f/f_0 = \pm 2.5 \times 10^{-5}$.

All the above tolerances are technically feasable. The problems of stability of the magnetic and accelerating high-frequency fields were carefully studied at JINR in 1968-1969 for the monoenergetic cyclotron project [7]. At that time we suggested a new method of the flat-top acceleration, which provided monoenergetic particles in a beam with the energy resolution $\Delta W/W \sim 10^{-4}$ [8]. Later the flat-top acceleration mode was used in the research of the beam orbit expansion effect at the electron model of the circular cyclotron (EMCC) [9].

It was decided to use a set of the first and second harmonics of the accelerating voltage because the specific construction features of the EMCC allowed acceleration only with dees whose length is near the working wave-length, even for the fundamental harmonic of the accelerating voltage. It the first and second harmonics of the accelerating voltage are used at optimum phase correlations, the energy gain per turn is

$$\frac{\Delta W}{\Delta W_{01}} = \cos\Phi - \frac{1}{a}\cos 2\Phi, \quad (3)$$

where ΔW_{01} is defined by the accelerating voltage amplitude U_{0i} and by the dee phase length θ_i

$$\Delta W_{0i} = 2U_{0i}\sin\frac{\theta_i}{2}, \quad (4)$$

$$a = \frac{\Delta W_{01}}{\Delta W_{02}}$$

is the gain energy ratio.

In accordance with "a", equation (3) defines the single-humped ($a \geq 4$) or two-humped ($a < 4$) curves symmetric about $\varphi = 0$. The location and the value of the extrema and the phase region, in which the energy spread at gaining does not exceed the permissible value, may be determined analytically.

The two-humped curve has its extrema at $\Phi_1 = 0(min)$ and $\cos\Phi_2 = \pm\frac{a}{4}(max)$.

The relative energy spread between the maximum and the minimum of the two-humped curve

$$\delta_{min} = 2\left[(\frac{\Delta W}{\Delta W_{01}})_{\Phi_2} - (\frac{\Delta W}{\Delta W_{01}})_{\Phi_1}\right] /$$

$$/ \left[(\frac{\Delta W}{\Delta W_{01}})_{\Phi_2} + (\frac{\Delta W}{\Delta W_{01}})_{\Phi_1}\right] \quad (5)$$

limits the possible choice of a values because the permissible energy spread δ must be larger than or equal to $\delta_{min} : \delta \geq \delta_{min}$.

A small parasitic phase shift transforms (3) to:

$$\frac{\Delta W}{\Delta W_{01}} = \cos\varphi - \frac{1}{a}\cos(2\Phi + 2\psi) =$$

$$= \cos\varphi - \frac{\cos 2\varphi}{a}\cos 2\psi + \frac{\sin 2\varphi}{a}\sin 2\psi, \quad (6)$$

i.e. there appears a shift of the extrema and an asymmetric part of the distorted plato, which leads to narrowing the permissible phase region. The location of the extrema and the width of the phase for the assigned phase shift and relative energy spread δ may be calculated by solution of the transcendentic equations. The calculated permissible phase shift region as a function of the energy gain ration "a" for $\delta = 0.001$ and ψ within the limits $0 \leq \psi \leq 0.1$ is shown in Fig. 2. It is evident from the figure that the azimuthal phase width of an accelerated bunch, whose energy spread is within 10^{-3} at $\psi = 0$, changes from 40.5° to 30.3°.

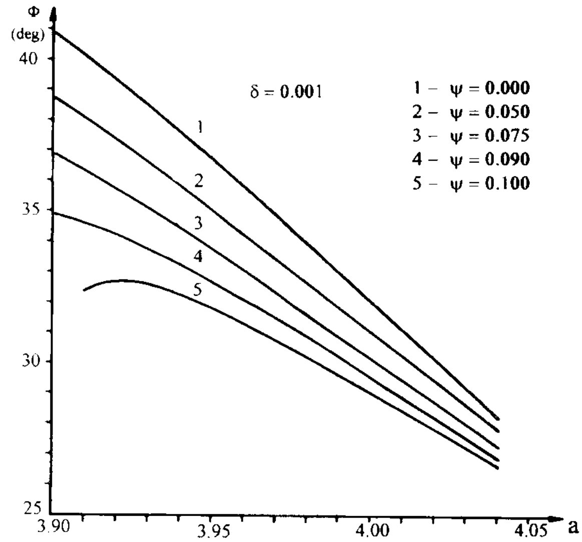

Figure 2: $a = \frac{\Delta W_{01}}{\Delta W_{02}}$ - energy gain ratio, Φ - beam phase width, δ - relative energy spread, ψ - phase shift.

The PSI accelerator complex collaborators made great advances in implementing the flat-top acceleration mode [10]. The use of a flat-top cavity resulted in an increased phase acceptance for the single-turn extraction mode of over 40^0 against 9^0 without the flat-top system. The extraction efficiency is improved to 99.98% while the energy spread of the bean reduced to lass than 5×10^{-4}.

After the PSI laboratory the flat-top acceleration mode was used at the ring cyclotron RCNP of the Nuclear Physics Institute in Osaca (Japan) [11] and at the sector cyclotron of NAC in Cape Town (South Africa), [12]. In both cases the phase acceptance at the last stage of acceleration grew up to 20^0 the average intensity increased by about two-fold and the beam extraction efficiency increased too.

3. Conclusion

The results obtained at the PSI accelerated complex were accompanied by constant upgrading of the R.F. system and increase in the cavity voltage. The accelerating R.F. system of the PSI sector cyclotron consists of four 50MHz main cavities and one flat-top 150-MHz cavity. The increasing of the main cavity voltage up to 730 kV lead, on the one hand as was said above, to essential positive results, such as an increase in the maximal average beam current up to 1.5 mA, an increase in the extraction efficiency, a decrease in the number of turn orbits to the total energy, but, on the other hand, the wall losses power, proportional to the square of the cavity voltage, considerably increased and exceeded 1.2 MW.

For one set-up, which is a unique research equipment these power losses are not a limiting critical factor, but for mass-produced industrial equipment they may cause a lot troubles. In our opinion the most suitable for nuclear energy production is the equipment which has an R.F. system with moderate energy gain per turn and due to an appropriately formed stationary magnetic field allows a big radial gain. Further experimental research and full-scale modelling are necessary to answer exactly the posed question.

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