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RESONANCE PHASING OF THE PHASOTRON BEAM

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A problem to optimize a phasotron capture of the beam into the acceleration mode is considered. The numeric simulation of the accelerated beam dynamics and the experimental check by the initial operation of the JINR phasotron have revealed the effect of the resonance phasing of ions by a wave-like magnetic field during the first phase oscillation of particles. Making use of the effect allowed us to increase considerably the mean rate of the energy gaining and the axial beam focusing in the central zone of the machine. The principle problem of structural separation of acceleration and magnet system elements in the central zone has been solved for phasotrons with the spatial variation of the magnetic field.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

Резонансная фазировка пучка фазотрона

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Рассмотрена проблема оптимизации фазотронного захвата пучка в режим ускорения. В результате численного моделирования динамики ускоряемого пучка и экспериментальной проверки физпуском фазотрона ОИЯИ был обнаружен эффект резонансной фазировки ионов волнообразным магнитным полем в процессе первого фазового колебания частиц. Использование эффекта позволило существенно увеличить средний темп набора энергии и аксиальную фокусировку пучка в центральной зоне установки. Решена принципиальная проблема конструктивного разнесения в пространстве элементов ускоряющей и магнитной систем в центральной области фазотрона с вариацией магнитного поля.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

In a classical synchrocyclotron the intensity of the beam captured into acceleration is limited in the phase motion by two factors/1/.

(i) The initial values of the phase (ϕ_0) and its time variation rate ($\dot{\phi}_0$) for particles of the accelerated beam must be obtained within the separatrix.

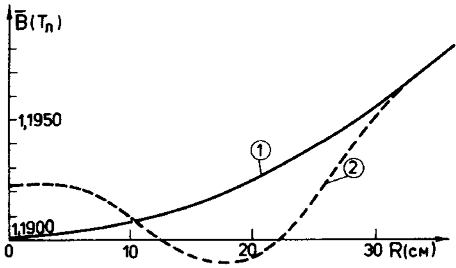

Fig.1. The mean magnetic field. 1 — smooth field, 2 — new field.

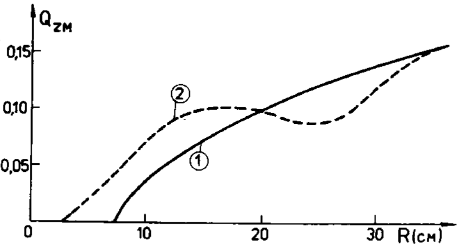

Fig.2. The frequency of axial oscillations. 1 — smooth field, 2 — new field.

(ii) The kinetic energy of ions during the 1st synchrotron oscillation must not reduce to values at which losses on the injector and losses due to scattering on the residual gas drastically grow.

In a phasotron with the spatial variation of the magnetic field /2/ the situation is aggravated by a smaller longitudinal beam focusing (parameter $K = -\frac{d\ln f}{d\ln E} \to 0$, where f is the frequency of revolution, E is the total energy of particles) and by absence of the magnetic axial stability in the central zone. Reduction of the parameter K (making it nearer to the cyclotron mode) is due to the increase of the mean value of the magnetic field over the radius(Fig.1, curve 1). Absence of the axial focusing (Fig.2, curve 1) is due to the increase of the mean field at small (or zero in the centre) values of the variation if elements of the acceleration and magnet systems are separated in the space (spiral iron pieces are not put inside the dee) /3/. A weaker focusing increases the probability of axial losses of particles. The radial quality of the beam deteriorates. Requirements to the mediam plane symmetry of the magnetic field and to the minimal amplitude of the accelerating r.f. voltage become stricter ($\bar{B}_R \sim$ 0.05-0.10 mT, $v_{min} \sim$ 20 kV for the JINR phasotron /4/). The threshold value of the accelerating voltage amplitude appears as a result of necessity of using the electric focusing in the central zone of the phasotron /5/. Reducing the value of K leads to a close tolerance for the deviation of the mean magnetic field from the required dependence ($\Delta\bar{B} \sim$ 0.4 mT for the JINR phasotron /6/) at a random form of this deviation.

Isochronous cyclotrons (K = 0) are devoid of above problems, because their accelerating voltage is much higher than that of a phasotron. It allows the focusing of ions at the first revolutions without the return of particles to the centre (absence of phase oscillations).

While revising theoretical concepts for the first phase oscillation on the basis of numerical calculations /7/, we have found a new law of the mean magnetic field variation along the radius for the JINR phasotron (Fig.1, curve 2). This law allows an acceleration mode with a reduced voltage amplitude (25-35 kV) with a significantly larger tolerance for violation of the median plane symmetry of the magnetic field ($B_R(Z = 0) \sim 0.3$-0.5 mT). The novelty is in abandoning the classical phase stability concent which implied absence of the transition through the critical energy and a slow variation of the phase equation parameters during the first oscillation. In the new mode at a fast (as compared with the period of synchrotron oscillations) transition through the critical energy zones ($K = 0$) the phase velocity and phase range of particles drop for the given phase volume of the beam due to increasing effective mass $M_{ef} = \frac{E}{(2\pi f)^2 K}$ /8/. This phase volume is retained in the range of accelerating phases, which results in a higher mean rate of the energy gaining and a weaker effect of the return to the centre. The necessary magnetic axial focusing of the beam (Q_{ZM}) at the first revolutions is provided by a decrease of the field along the radius (Fig.2, curve 2).

The resonance character of the effect of the wave-like shape of the new magnetic field (bump) on the beam is seen from the particle distribution over the value of the first radial minimum (R_{min}, Fig.3) at different values of the bump wave length

$$\bar{B}(r) = \bar{B}_T(r) + \Delta B_m \cdot J_0\left(\frac{r}{\lambda}\right) \exp\left(-\frac{r}{a}\right), \qquad (1)$$

where $\bar{B}_T$ is the classical smooth field /2,3/, ΔB_m is the bump amplitude (~ 10 mT), J_0 is the Bessel function of the zero order, a is a parameter (~ 66 cm). The optimum value of λ corresponds to a characteristic radial size of the first phase oscillation ≈ 48 cm.

The bump parameters are adjusted in order to obtain maximum values of R_{min} and Q_{ZM} at minimum losses for phase motion ($\approx 10\%$) with respect to the smooth (monotonously increasing) field mode. Numerical calculations show that despite the shift of the resonance value of the free radial oscillation frequency $Q_R = 1$ from the centre to the radius ≈ 20 cm (JINR phasotron) the increase of the amplitude of those oscillations is hardly noticeable until the 1st harmonic amplitude of the axial component of the magnetic field $B_{m1} < 0.5$ mT and the accelerating voltage amplitude $V > 20$ kV.

Employing a new shape of the field in a spatial variation phasotron allows one to solve the principle problem of separation of acceleration and magnet system elements in the central zone of the accelerator (there is no need to place spiral iron pieces inside the dee to achieve the axial focusing as it is done in the NEVIS phasotron with a smooth field /3/). This cancels many technical problems and makes the operation of the machine much more reliable.

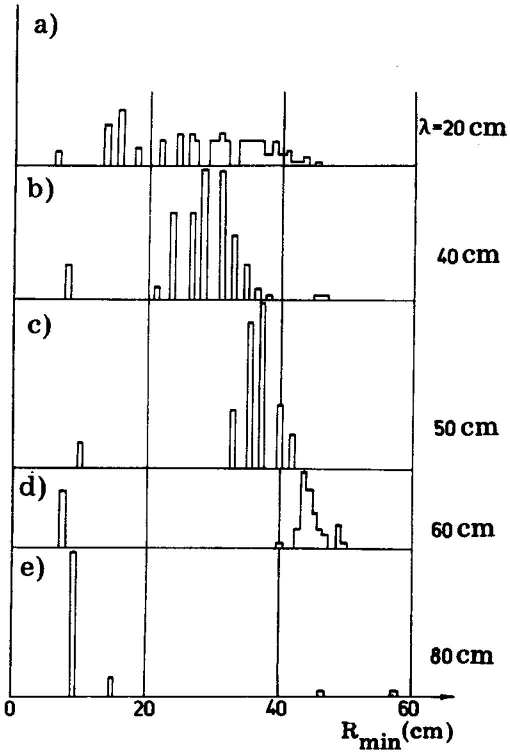

Fig.3. The resonance adjustment of the bump wave length to the maximum value of the first radial minimum of particles.

The principle difference between the new shape of the field proposed for phasotrons and other bumps previously employed for increasing the axial stability [6,9,10] is in a sign-variable character of the parameter K variations (which is analogous to a strong focusing for the phase motion at the increase of the absolute value of K by an order of magnitude). The forms of field bump considered are related either to large values of λ (Fig.3e), or to non-optimal changes of the bump shape owing to radius, which significantly limits the permissible radial gradient of the field as to the effect of phase losses of beam particles.

The discovered mode of phasotron capture is experimentally checked by a successful initial operation of the JINR phasotron where the bump-field was used (Fig.1). Calculations of the beam intensities for various amplitudes of the accelerating voltage are in good agreement with measurements performed at the operating accelerator (Fig.4). The field bump allowed the particle beam to pass through the central zone of the phasotron at $\bar{B}_R \geq 0.6$ mT and V = 30 kV.

In future we are going to study the application of this mechanism of the resonance beam phasing for correlation of the longitudinal movement of particles with the parameters of the acceleration system over the whole range of radii, especially at the stretching of the beam by C-electrode [11]. Thus, there is a possibility of employing the wave-like field as an alternative to variations of the energy gaining for realisation of the phase compression effect in the cyclotron [12].

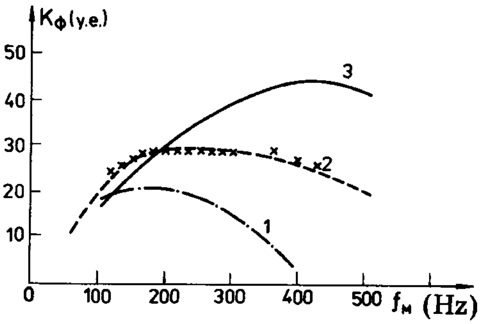

Fig.4. The beam intensity after the first phase oscillation as a function of the repetition frequency rate of the accelerating system. 1 — 20 kV, 2 — 30 kV, 3 — 50 kV, xxx — beam intensity measurements.

Conclusion

The proposed resonance beam phasing in the central zone of the phasotron with the magnet field variation is experimentally checked at the JINR phasotron. The results confirmed the principle possibility of using structurally separated focusing and accelerating systems in phasotrons with the spatial variation of the magnet field.

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