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VARIABLE CHARGE HEAVY ION SYNCHROTRON THEORY

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Summary

A new approach is developed to solve the problem of heavy ion synchrotron acceleration. As is shown, the circular strong-focusing structure of a resonable width provides the substantial charge confinement with a spread of $|\Delta q|/q_0 = 0.1\div0.2$. Charge-exchange injection on the internal target makes it possible to overcome the limitations imposed by the Liouville theorem. The synchronous ion acceleration with charge spread is considered possible and the average beam charge is supposed to increase by the gradual stripping of the orbital electrons up to the complete stripping of them.

The operation modes considered appear to be most suitable to accelerate as heavy ions as that of uranium.

1. Introduction

Heavy ion acceleration up to the energies of hundreds of MeV/nucleon and even more appears to be one of the main goals of a number of labs [1-4]. Such beams are of a great importance for a researcher working in the field of nuclear physics, especially, dealing with studies of nuclear matter at high densities and temperatures. Acceleration of very heavy ions such as that of uranium is of a growing interest to-day.

The report presented is a brief review of theoretical papers, published recently in the USSR, on charge-changing heavy ion acceleration problems [5-9]. By giving up the idea of constant accelerating charge one is able to get a loophole to increase phase density and beam intensity as well as to reduce the circumference of a machine. However, the engineering of all the above turns out to be more laborious and requires the solution of a number of new problems.

2. Closed orbits and betatron stability

Consider the closed orbit of an ion with a momentum p_0 and a charge q_0 which coincides with the vacuum chamber axis. The radial orbit variation of an ion with a momentum $p_0+\Delta p$ and a charge $q_0+\Delta q$ is determined in the linear approximation by

$$\Delta r(s) \simeq \psi(s)\left(\Delta p/p_0 - \Delta q/q_0\right), \qquad (1)$$

where $\psi(s)$ is the dispersion function. We are interested in the case $|\Delta p|/p_0 \ll |\Delta q|/q_0$. The orbit compaction of ions with different charges requires magnetic structure designing with lowest possible dispersion. One can easily obtain $\psi_{max} \lesssim 0.5$m for the synchrotron with a circumference of several hundred meters. A radial increase of the vacuum chamber of not more than 10 cm is needed in order to confine the uranium equilibrium spectrum in the energy range of $1\div2$ MeV/nucleon. The charge dependence of betatron oscillation frequencies appears to be the main feature of the transverse motion of differently charged ions. Betatron stability conditions as well as various problems of magnetic structure designing are considered in [9]. As is known, there is transverse stability in the linear approximation in the structure with compensated chromaticity. Compensating sextupole components of magnetic field should better be included in all the ring magnets responsible for the strong focusing of a beam. The $(\Delta q/q_0)^2$ effects are compensated, if necessary, by the octupole field.

Ion charge-exchanging does not give rise to radial betatron oscillations if it occurs at an azimuth s_0 such as to satisfy the equation:

$$\psi(s_0) = \psi'(s_0) = 0 \qquad (2)$$

Equation (2) is fundamental, indeed, in charge-changing operation of a synchrotron. The magnetic structures satisfying this equation are well known [10].

3. Synchronous phases, momenta, and longitudinal stability

Ions of different charges could be synchronously accelerated by one RF system. Every charge component has both the synchronous momentum $p_s(q)$ and phase $\varphi_s(q)$ of its own. It is easy to obtain that the spreads of both the synchronous momenta Δp_s and phases $\Delta\varphi_s$ satisfy the following equations:

$$\Delta p_s/p_{0s} \simeq -\alpha\gamma_0^2\,\Delta q/q_0 \qquad (3)$$

$$\Delta\varphi_s \simeq \mathrm{ctg}\,\varphi_{0s}\cdot\Delta q/q_0\ , \qquad (4)$$

where $\alpha \ll 1$ is the momentum compaction factor, γ_0 the relative energy, and the zero index relates to the ions with a charge q_0.

It is the fact that the relative spread of synchronous momenta turns out to be much less than that of charges,

$$|\Delta p_s|/p_{0s} \ll |\Delta q|/q_0\ ,$$

which is extremely important. The charge spectrum does not induce the significant energy spread of a beam, which is due to the orbit compaction in the strong-focusing synchrotrons.

The separatrices of differently charged ions are almost entirely coincide.

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Multip le charge-exchanging induces stochastic synchrotron oscillations which could be reduced by a proper choice of the acceleration parameters. Due to average ion charge increasing, the additional adiabatic damping of phase oscillations occurs :

$$\eta_m(q_0) \sim q_0^{-1/4} ,$$

which is, nevertheless, higher in value than stochastic exitation. In order to accelerate a multicomponent beam of variable average charge $q_0(t)$, one should follow the RF modulation law:

$$f(t) = h e q_0(t) c^2 B_0(t) E_0^{-1}(t) , \quad (5)$$

where h is the harmonic number, and B_0, E_0 the magnetic field and total ion energy on the vacuum chamber axis, respectively. The equilibrium voltage depends on the average charge variation rate

$$\bar{V}_{0s} = \bar{V}_{0s}^{(0)} \left(1 + \frac{\dot{q}}{q_0} \cdot \frac{B_0}{\dot{B}_0}\right) , \quad (6)$$

where

$$\bar{V}_{0s}^{(0)} = R_0 L_0 \dot{B}_0 \quad (7)$$

is the equilibrium voltage when accelerating constant-charge ions.

Equation (6) follows from the requirement of the confinement of the charge $q_0(t)$ on the central orbit of a radius R_0 over all the acceleration time.

4. Possible operating modes

Working out the theory of heavy ion acceleration with charge spread and gradual average charge-changing has been enhanced due to the desire of overcoming the difficulties natural to the common acceleration scheme of a monocharged beam.

As is known, the intensity of a heavy ion sources is rather low. Besides, there is always considerable stripping loss prior to ion injection. Ion sources are capable of providing long pulses whereas the synchrotron injection is strictly limited in time, i.e., ion source operation modes are not adequate to peculiarities of synchrotron beam capture. Because of this the pulsed synchrotron intensity is several hundred times lower than that ultimately available according to the well known space charge limitations.

One should also remember that ions are not highly charged at low injection energies so that their interaction with electrical and magnetic fields is quite weak, much weaker than that of protons.

The application of all the above concepts makes it possible to obtain the pulsed intensity ten or even several hundred times higher due to getting rid of stripping losses as well as to ion storage at injection. The final momentum in synchrotrons with a constant value of $B_{0max} \cdot R_0$ increases by a factor of the ratio of the final charge to the ion injected charge.

The three possibilities of operation below presented are based on the concepts developed above. They are:

a. Acceleration of a charge spectrum

The intensity of a charge spectrum is several times higher than that of a single charge component, e.g., it increases by a factor of five for uranium. Accordingly, the radial aperture of a vacuum chamber also increases by $2\psi|\Delta q|/q_0$. It is worth accelerating very heavy ion beams injected at high-enough energies. For example, the average uranium ion charge q_0 at an energy of 10 MeV/nucleon is 70, so, in order to accelerate five charge components with a charge spread of $|\Delta q|/q_0 = 2$, one should increase the radius of a vacuum chamber by 3 cm at ψ =50 cm. It is possible in this simple case that the magnet structure have no sections with ψ =0, however, the chromaticity should be zero.

b. Ion storage

One may transform the dependence of the beam current from an injector with time in such a way as to better correspond to the capture process of a beam in a synchrotron which, in fact, means storage. It is also th ought to be possible to store a beam increasing its phase density. The storage in this case is similar to the charge-exchanging injection of H^- ions [11].

When storing the stripper is at an azimuth at which equation (2) is satisfied. The ion beam of a low charge q^* is transported from the injector to the vacuum chamber axis and passes through the stripper (see Fig.1). The thickness of the stripper should be adequate to obtain the equilibrium charge distribution just after a single pass through it. After passing through the stripper the average beam charge is $q_0^{(1)}$, and the charge spread including almost all the ions being $2|\Delta q|$ = 10÷12.

The magnetic field on the chamber axis is such that the ions with a charge $q_0^{(1)}$ turn just along it. The ions with different charges turn along the closed orbits of their own according to equation (1). On completing a turn the ions pass through the stripper again. Some ions change their charges at this, however, the ion charge distribution conserves. A second turn is in general the same as a first one in spite of the fact that the radial coordinates of some ions correspond to their new charges. The width of a beam does not change. Thus the circulation process continues up to tens or even hundreds of turns.

The ions with a charge q^* continuously emerge from the injector and, getting stripped, get captured. Charge-changing injection makes it possible to overcome the limitations imposed by the Liouville theorem. The phase density of a beam increases almost linearly when storing.

The ionization energy losses due to the multiple passage through the stripper is the main factor limiting the storage time. Working out an adequate means to compensate such losses may provide the phase density several hundred times higher.

c. Gradual stripping at acceleration

Gradual beam stripping increases the

acceleration effect. A synchrotron accelerator with stripping is equivalent to a common one having a high energy injector. High injection charge states are available in this latter case, and additional stripping is not needed.

In order to strip ions the stripper should be very thin to provide the charge state of a beam lower than the equilibrium one. It appears here that charge-exchanging is nothing more than stripping, which is, of course, desirable.

Charge-exchanging acceleration turns out to be an example of the Markov random process. In order to better understand the transformation of a charge spectrum, we will consider the following simple example. Let charge-exchanging be nothing more than single electron stripping, and the ion lifetime in a charge state does not depend on q, i.e., $n\sigma v$ = Const (n is the average circumference density of stripping media, σ the stripping cross section, and v the velocity of an ion). Then the charge spectrum could be discribed as follows:

$$\bar{Y}_{q_0^{(i)}+k} = e^{-\zeta} \sum_{\ell=-m}^{m} \frac{\zeta^{k-\ell}}{(k-\ell)!} \bar{Y}_{q_0^{(i)}+\ell}(0) , \qquad (8)$$

where $\zeta = n\sigma v t$, t being time and $\bar{Y}_{q_0^{(i)}+\ell}(0)$ the spectral components at injection.

The charge spectrum gets broader with time, but one has here to keep in mind that the number of charge states in the magnetic ring of a given width increases as $q_0(\zeta)/q_0^{(i)}$, which follows directly from equation (1).

At real conditions the charge spectra undergo so called "self-focusing" because it is always true that $(\Delta\sigma/\Delta q)_{v=const} < 0$.

The average rate of change of the ion charge state $\langle \dot{q} \rangle = \sigma n v$ is higher for the ions of low-charge states and vice versa. This was not taken into account in equation (8). The charge spectra found on the basis of the real charge-exchanging cross sections appear to be more compact.

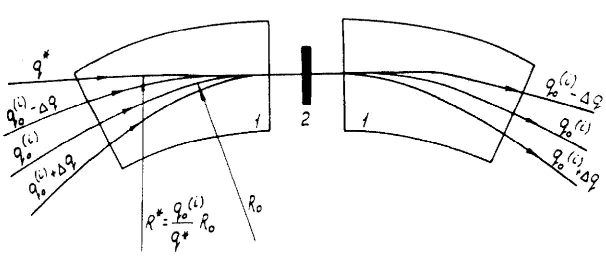

Fig.1. Storage injection scheme:
1 - bending magnets; 2 - stripper

To minimize the probability of multiple electron loss, one should better use light gases for stripping. A stripper thickness of $10^{-1} \div 10^{-2}$ $\mu g/cm^2$ at $\overline{\sigma v} = 10^{-8}$ $cm^3.s^{-1}$ provides almost complete ionization. The average lifetime of an ion in a given charge state is of the order of $\sim 10^3$ turns.

At the energies of several hundreds of MeV/nucleon even most heavy ions get fully stripped so that they transform to nuclei.

The considered approach of storing and synchrotron acceleration of heavy ions clearly illustrates great possibilities of such well-known fundamental principles of particle acceleration as those of strong-focusing and phase stability.

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