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INJECTION AND ACCUMULATION METHOD IN THE TARN

T. Katayama, T. Nakanishi and S. Yamada
Institute for Nuclear Study, University of Tokyo
Tanashi, Tokyo 188, Japan

TARN is an accumulation ring of heavy ion beam from the Sector Focusing Cyclotron. In order to obtain a high-intensity stacked beam, both of multiturn injection and RF stacking methods were applied to the TARN. In this injection scheme, about 20 turns of the beam was stacked in the transverse phase space using a horizontal multiturn injection system. The injected beam emittance was about 100 πmm·mrad. The injected ions were then stacked into longitudinal phase space by an RF field. Since the period for the stacking procedure is limited by the frequency of phase oscillation and the condition of adiabaticity, the repetition rate of RF stacking was 50 $\sim$ 100 Hz. The total gain of beam intensity is estimated at about one thousand.

In this paper, details of theoretical aspects of the injection and accumulation method are described as well as the experimental results.

Introduction

For obtaining a high-energy heavy ion-beam, it is most economical to use a synchrotron with an injector linear accelerator. A peak intensity of the linac beam, however, is rather poor for heavy elements such as uranium due to the ion source performance. Furthermore a synchrotron is in pulse operation and the period of injection is rather short, usually several tens of micro-seconds and as a result it is normally difficult to get a good beam intensity of heavy ions from a linac-and-synchrotron system.

One method to improve the intensity is to develop the high-current heavy-ion source, maybe with a low charge state. The ion beam with low charge state could be accelerated with a low velocity linac such as RFQ type and the research for this direction is now intensively pursued in our laboratory.

An alternative method is to add a storage ring between an injector linac and a synchrotron. In this case the repetition rate of the synchrotron can be reduced to nearly 1 Hz without the sacrifice, or even with the improvement of the beam intensity and the requirements for the synchrotron RF acceleration system and the vacuum chamber become easier. Also the beam spill-out time can be made long enough to perform efficient counter experiments by use of a long flat top in the magnet excitation of synchrotron.

In the high energy proton storage ring such as ISR, beam is stored by only the RF stacking method with a single turn injection in the betatron phase space. Comparing with the betatron phase space injection, the RF stacking method requires rather longer stacking period and it is not adequate to fill the beam in the storage ring from the injector with continuous operation. In this paper the combination of multi-turn injection and RF stacking methods is examined theoretically and the experimental results performed on the Test Accumulation Ring for Numatron, TARN, are presented.

Multiturn Injection Method

In the multiturn injection two pulse magnets are located upstream and downstream from the injecting position. The equilibrium orbit between these magnets is distorted by the bump fields and the distance between these two magnets should be a half of betatron wavelength in order to avoid any effect on the other part of the equilibrium orbit. The maximum distance and the collapsing rate of the closed orbit distortion is determined so as to optimize the beam intensity stacked in the betatron phase space. A constant collapsing rate of the bump fields is assumed here, since it gives the most efficient injection. In this case, the septum moves by a constant displacement of Δx at every revolution period, and therefore, an instantaneous acceptance changes its location, shape and area throughout the injection interval.

The nth instantaneous acceptance is a rectangle surrounded by following four lines;

$$x = x_n \ , \tag{1.a}$$

$$x = x_{n+4} \ , \tag{1.b}$$

$$y = x_{n+3} \tag{1.c}$$

and
$$y = -x_{n+1} \ , \tag{1.d}$$

where x_j represents the position of inner side of the inflector septum, and is given by

$$x_j = x_1 + (j - 1)\Delta x \ . \tag{2}$$

The area of the nth instantaneous acceptance, S_n, is described as

$$\begin{aligned} S_n &= (x_{n+4} - x_n)(x_{n+3} + x_{n+1}) \\ &= 8\Delta x \cdot [x_1 + (n+1)\Delta x] \ . \end{aligned} \tag{3}$$

If the emittance of the injector beam is large enough, heavy ions are possible to populate throughout the instantaneous acceptance, except on the region shadowed by the septum. Hence the area of the instantaneous acceptance without the shadow line is represented by

$$B_n = 2(4\Delta x - s)[x_1 + (n+1)\Delta x] \ . \tag{4}$$

where s denotes the septum thickness. Consequently, the nth filling factor becomes

$$f_n = \frac{B_n}{S_n} = 1 - s/(4\Delta x) \ , \tag{5}$$

and is constant with n. It is found from this equation that the larger Δx gives the more efficient injection. In the case of larger B_n, however, the effect of the finite beam emittance becomes serious. Then, the nth filling factor decreases with increasing n as described by following equation;

$$f_n = \frac{\pi\beta E}{S_n} = \frac{\pi\beta E}{8\Delta x[x_1 + (n+1)\Delta x]} \ , \tag{6}$$

where the half width of the injector beam at inflector exit, d, is assumed to satisfy the following equation;

$$d = 4\Delta x - s \ . \tag{7}$$

Thus, it is clear that the smaller Δx gives the more efficient injection at large B_n, whereas the large Δx is preferable at small B_n as described above.

The collapsing rate of the closed orbit distortion, therefore, should be chosen so as to optimize the filling factor, which is a ratio of the total beam area to the total acceptance. The injector beam width, on the other hand, is determined by the focusing system installed between the injector cyclotron and the ring. The minimum beam size (half) at the inflector exit is limited to be about 1 mm mainly by the gap and the length of the electrostatic inflector.

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RF Stacking Method

The procedure of RF stacking is as follows. The beam from the cyclotron is transported to the ring through the beam transport line with the optical matching system, and is injected by a multiturn method (Injection). Then the RF accelerating voltage is put on and the beam is captured in the stable region of the RF acceleration (Capture). The RF voltage and the frequency are adiabatically changed and the beam is moved to the stacking orbit (Acceleration). The RF voltage is put off and the beam is remained on the stacking orbit (Deposit). There are two RF stacking methods.[1] One is a non-repetitive stacking method where every new injected beam is deposited at the stack bottom. The other is a repetitive stacking schemes, in which every injected beam is carried through the stack up to its top. The stacking scheme of the repetitive method is obviously much simpler than that of the non-repetitive method, and nearly the same phase space density can be obtained by two methods.[2] Therefore we adopt the repetitive stacking method.

Phase Space Area of the Injected Beam

The area and shape of the longitudinal phase space of the beam, which is injected into the TARN by the multiturn injection method, is estimated considering the energy spread of the beam from the injector cyclotron and the debunching effect during a period of beam transportation and multiturn injection. Energy spread of the beam in the isochronous cyclotron such as INS SF Cyclotron, is mainly due to the phase spread of the beam at the crest of RF field. Measurement of the phase spread of the bunch in the cyclotron shows that a full width is less than 4°. Then we assume that the energy spread ($\Delta T/T$) is less than 2×10^{-3}, where T denotes a kinetic energy per nucleon and hereafter it is assumed to be 8.0 MeV in this paper. Energy spread (ΔT) is calculated at ± 8 keV and phase space area of the beam is 0.88 (rad·keV).

After the ejection from the cyclotron, the beam is transported to the TARN by the distance of 40 m and then injected in the TARN by a multiturn injection method. During a period of this flight, beam is debunched due to the velocity difference of particles in the bunch. This phase spreading, however, does not involve any change of energy spread. Total path length is 1300 m for the case of 40 turn injection and bunch width after the multiturn injection is ± 16 nsec which corresponds to the phase spread of ± 0.86 rad for the RF frequency of 8.5 MHz.

Capture

The initial value of RF field is chosen so that the separatrix well cover the energy spread of the injected beam, and is rather freely chosen within the limits satisfying the above condition. Bucket height of the separatrix is given by

$$H = (h\varepsilon eV)^{1/2}\ Y\,\frac{\beta}{h}\left[\frac{E}{\pi|\eta|}\right]^{1/2}, \quad (E,\ H;\ \mathrm{keV}) \qquad (8)$$

where h, ε, V, β and E represent a harmonic number, a charge to mass ratio, a peak RF voltage, a beam velocity in unit of light velocity and an energy of a nucleon, respectively. Y is a function of equilibrium phase ϕ_s and is $\sqrt{2}$ for the stationary bucket ($\phi_s = 0$). η is defined as

$$\eta = \gamma_{tr}^{-2} - \gamma^{-2}, \qquad (9)$$

where γ_{tr} is a transition energy in unit of the rest mass of the nucleon. Substituting numerical values for the TARN parameters, $h = 7$, $\beta = 0.1298$, $\gamma = 1.0085$, $\gamma_{tr}^{-2} = 0.2787$, $E = 939$ MeV, we obtain a required minimum RF voltage for covering an energy spread of the beam by a separatrix as

$$\varepsilon eV = 31.3\ \mathrm{eV}\ .$$

or $$eV = 87.6\ \mathrm{eV} \quad (\varepsilon = 0.357 \text{ for } N^{5+})\ .$$

However we adopt a sufficiently large RF voltage comparing with the above value for the initial value, which is the same as the accelerating voltage. On the other hand the period of phase oscillation during the capture process, must be much larger than the locking time of the phase lock loop in the RF system. We choose a locking time as 100 μs considering the FM noise of the system. Finally the RF voltage at the capture process is chosen as 1100 volt, at which the period of phase oscillation is 1.13 msec.

Acceleration

The rate of momentum change for the synchronous particle is given by

$$\frac{dP/dt}{P} = \frac{1}{E_s\beta^2}\cdot f_{rev}\cdot eV\cdot \sin\phi_s\ , \qquad (10)$$

where E_s is total energy of the synchronous particle (939 MeV), f_{rev} is a revolution frequency around the ring (1.227 MHz), V is the RF voltage and ϕ_s is the synchronous phase angle. It is obvious that the large value of $V\cdot\sin\phi_s$ is preferable for carrying every injected beam from the injection orbit to the stacking orbit as early as possible. Detailed calculation[3] shows that the values of $\sin\phi_s$ much larger than 0.5 lead to bad stacking efficiencies, then $\sin\phi_s = 0.5$ is selected. The RF voltage is, however, limited by the tolerances for programming the voltage and frequency in the low level RF electronics system. Finally we choose a value of V at the acceleration stage as 1.1 KV. The numerical result of the rate of momentum change, $\frac{dP/dt}{P}$, is 1.52×10^{-2} (msec^{-1}). The fractional momentum variation corresponding to the distance from the injection orbit to the bottom of the stacking orbit is designed at 3.82 %, then it is required 2.5 msec to change the momentum of the injected beam to that of the bottom of the stacked beam. The revolution-frequency difference between the injected and stacked beam at the bottom is calculated at 32.6 kHz and the corresponding RF frequency difference is 228 kHz.

Deposit

During a period of acceleration from the bottom to the top of the stacked region, the RF voltage is adiabatically reduced to the final voltage. This reduction of RF voltage is necessary because the high RF voltage brings about undesirable large momentum spread of the stacked beam when the separatrix is moved to the top of the stacking orbit. This momentum spread is evaluated in the following paragraph in detail.

The final RF voltage is determined so that the area of the separatrix is just equal to or is larger than the longitudinal phase space area of the injected beam, 0.88 (rad·keV). For the constant $\sin\phi_s$ of 0.5, the required final RF voltage must be larger than 0.148 volt. However this small RF voltage requires a much longer time, for the deposit period. This is because, first, the adiabaticity in the change of RF voltage is required and, second, the synchronous phase angle must be kept constant at 30 degrees during a process of deposit. On the other hand, the life time of the beam in the ring is determined by the pressure in the vacuum chamber, say 1×10^{-10} torr in the TARN, and is estimated at 1 sec for the survival rate of 90 % for this pressure. Then slow repetition rate of RF stacking may result in a low intensity in the ring. Typical stacking rate is 50 Hz and the final voltage at this case is 100 V which is within a controllable region by the amplitude regulation system with a dynamic range of 100.

The necessary time to change adiabatically from the initial bucket to the final one is given by

$$T = \frac{1+\eta}{2(1-\eta)} \left(\frac{1}{\omega_{p_2}} - \frac{1}{\omega_{p_1}} \right) , \tag{11}$$

where ω_{p_1} is the angular frequency of phase oscillations associated with the initial bucket, ω_{p_2} is that of the final bucket and η is a quantity related to the phase space efficiency of the process. Since ω_{p_1} is larger than ω_{p_2}, the time T is almost independent of the initial conditions. Assuming V = 100 (Volt) and $\eta = 0.9$, we obtain T = 6.3 ms.

Momentum difference between the bottom and the top of the stacked region is designed at 2.469 % and hence the RF frequency must be changed by 149 kHz for this acceleration. In order to keep $\sin\phi_s$ as 0.5 for the RF voltage of 100 volt during the acceleration, the time derivative of the frequency must be 8.8 kHz/msec and then the time required for the deposit is 17 msec.

Energy Spread of the Stacked Beam

At every acceleration, the bucket passes over the stacked particles and disturbs their energy oscillations. The mean beam energy decrease, ΔE, of the stacked beam due to this effect can be derived from Liouville's theorem: it is found[4] that after n passages

$$\Delta E = \frac{nA}{2\pi} = n\alpha(\Gamma)\delta E_{st} , \tag{12}$$

where A is the invariant bucket area in eV and $\alpha(\Gamma)$ is the moving bucket factor depending on the quantity

$$\Gamma = \sin\phi_s . \tag{13}$$

The averaged width δE_{st} of a stationary ($\Gamma = 0$) bucket is given by

$$\delta E_{st} = \frac{4\beta}{\pi} \sqrt{\frac{2eVE_o\gamma\epsilon}{\pi|\eta|h}} . \tag{14}$$

Substituting the numerical values for TARN parameters, we obtain δE_{st} = 11.3 (keV) and ΔE = 3.75 n (keV), respectively. The available space for the beam stacking is designed as the corresponding energy spread of 392 (keV), hence the maximum stacked number is calculated at 104.

The energy dispersion $\langle\delta E\rangle$ introduced in an initially monoenergetic beam due to the n passages of the bucket is given by

$$\langle\delta E\rangle = \sqrt{n}\,\delta E_{st} \cdot \sin\phi_s . \tag{15}$$

The numerical result is $\langle\delta E\rangle$ = 56.4 keV and the ratio of $\langle\delta E\rangle$ to ΔE is 0.14 which appears to be quite acceptable.

Combination of Multiturn Injection and RF Stacking Method

It is an important result that the momentum spread after the RF stacking is approximately proportional to the stacking number in synchrotron phase space. Assuming m as a stacking number in synchrotron phase space, the RF stacking requires an aperture of

$$x_s = 2x_\beta + 0.24\, x_{eq} \frac{\Delta p}{p_0} \cdot m \tag{16}$$

where x_{eq} is a dispersion function, $\Delta p/p_0$ is a momentum spread of the injected beam, and x_β is an amplitude of betatron oscillation after the multiturn injection. The factor of 0.24 is due to the synchrotron phase space area in the deposit process. Thus, the total aperture required for the combined method is

$$x_t = x_s + 2x_\beta + x_d \tag{17}$$

where the symbol x_d represents a dead space due to a leakage flux of the bump magnets. The value of m must be chosen so that x_t may not exceed the available aperture in the ring doughnut.

Substituting the numerical values of the TARN parameters, a total stacking number in both spaces are obtained as a function of x_β. As shown in Fig.1, the number has a peak near x_β = 20 mm. This value corresponds to about 1/6 of the available aperture, $(x_t - x_d)$. At this point, we can obtain about 1900 times higher current than the injector beam, whereas the multiturn injection alone gives about 120. Thus, the multiturn injection scheme with x_β = 20 mm is adopted. In this case, the circulating heavy ions are spatially distributed around the central orbit as shown in Fig.2.

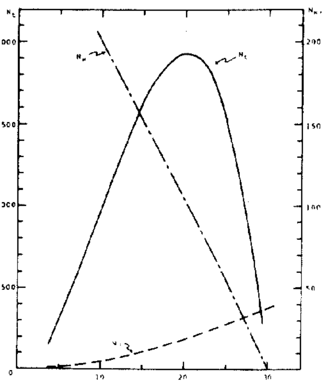

Fig.1 Total stacking number N_t, versus half aperture used for multiturn injection method, x_β, stacking numbers in betatron and synchrotron phase spaces are also shown.

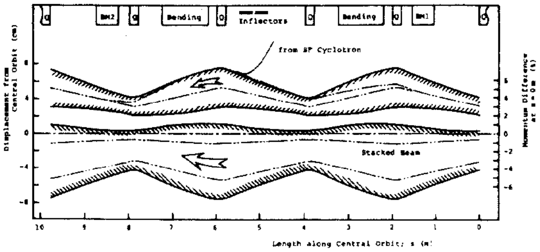

Fig.2 The calculated beam envelopes in the TARN (solid lines) at x_β = 20 mm. The dot-dashed line is a central orbit. The closed orbits for various momentum (injection, stack top and stack bottom) are also shown (—·-—).

Experimental Results of Beam Accumulation

α particles of 28 MeV were injected in the TARN from the cyclotron. The injected beam is observed by electrostatic monitors, ESM, installed in the ring. Figure 3-a shows the single turn injected beam with a pulse width of 80 μs. (The injected beam was stopped by a Tantalum plate at a downstream position to the ESM.) The pulse height of the signals corresponds to the beam intensity of about 1×10^{13} particles/sec. This intensity is identical with 1×10^7 circulating particles in the ring, since the revolution frequency of the ions is chosen at about 1.1 MHz.

The ν_x-value of the ring was adjusted around 2.25, and therefore, the injected beam striked against the inflector electrodes after 4 revolutions. Without tantalum stopper, the output signal of the ESM grows up about 4 times greater than the single turn case. (Fig.3-b)

According to the field decrease of the bump magnets, ions are accumulated in the betatron phase space. The output signal of the ESM increases linearly up to about 2 × 10^8 circulating particles in the ring (about 2 × 10^{14} particles /sec) as shown in Fig.3-c. The width of the multiturn injected beam is about 35 mm (FWHM), and the beam emittance after the injection is calculated at 153 mm·mrad. After the multiturn injection, beam was stacked in the longitudinal phase space.

The stacked beam cannot be observed by the ESM, since the beam is debunched due to an intrinsic momentum spread. A movable plastic scintillator is used for measuring the beam profile after the RF stacking. Figure 4 shows an example of these measurements. The position of the multiturn injected beam is indicated in the upper part of figure and also in the figure is shown the stacked beam profile.

An intensity gain factor more than about 10 was obtained by applying the RF stacking method. An overall intensity gain after the combined method is about 200. The resultant number of the circulating particles is estimated to be about 2 × 10^9.

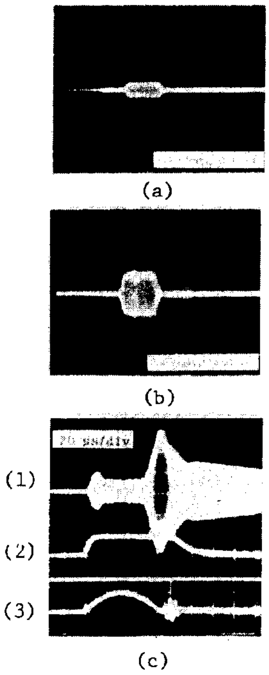

Fig.3 Observed beam signals by ESM installed in the storage ring; (a) single-turn injected beam (∿ 1 × 10^7 circulating particles in the ring), (b) four-turn injected beam, and (c-1) Injected beam in multiturn, (c-2) current form of kicker magnet and (c-3) current form of bump magnets, 20 μs/div.

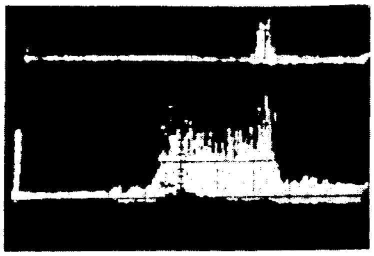

Fig.4 Beam profiles after the RF stacking process. Ions of He^{2+} are multiturn injected (top of the figure) and RF stacked in the storage ring.

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