INJECTION INTO THE ACCUMULATION RING FROM THE INS-SF CYCLOTRON

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Abstract.- The construction of a Test Accumulation Ring for NUMATRON Project, TARN, was finished and the first injection test was performed successfully in August, 1979. For testing the beam accumulation technology by a combination of multiturn injection and RF stacking, He^{2+}, H_2^+ and H^+ beams of 7 MeV/u were used so far. Through this work, various technical problems for the NUMATRON have been investigated.

1. Introduction.- Several years ago, a high energy heavy-ion accelerator project was proposed in order to respond to many demands not only in the field of nuclear physics but also in many other fields of fundamental researches and applications, which is named NUMATRON Project.[1)]

The energy-mass capability of the NUMATRON is shown in Fig. 1 together with those of the other machines in operation, under construction and in planning stage in the world. All of the accelerator higher than 200 MeV per nucleon consist of injector linac and synchrotron. At the design stage of this type of accelerator complex, a synchrotron with an accumulation ring is the most preferable for obtaining an expected high-intensity beam, considering present ion-source technologies and low duty factor of synchrotron.

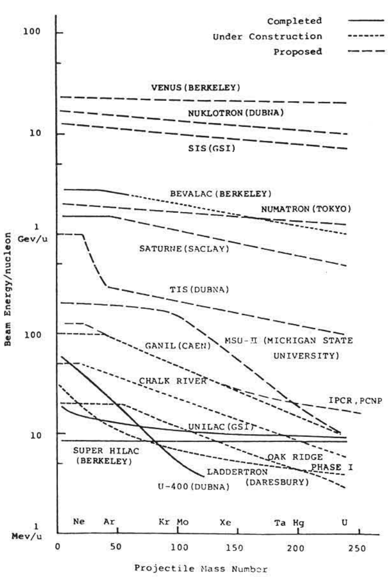

Fig. 1 Mass-energy capability of heavy-ion accelerators.

In order to investigate various related problems, several preparatory works have been carried out. One of the most important achievements is the construction of a test accumulation ring of 10 m in diameter[2)] as shown in Figs. 2 and 3. The SF cyclotron as the injector has been in operation since 1974. Ions from hydrogen to neon, e.g. $^{14}N^{5+}$ of 8.5 MeV/u, are injected and stacked into the TARN. The beam of $^{14}N^{5+}$ was supposed in the design calculations. Most of the test experiments were done by use of He^{2+}.

2. Beam Transport and Injection System.- The beam transport system consists of the following four sections: momentum analyzing section which gives the momentum resolution ($\Delta p/p \sim 1 \times 10^{-3}$) required for the RF stacking, momentum matching section where doubly achromatic beam (η_h=1.61 m, η'_h=0) is produced, dispersion-free matching section of transverse phase space to adjust the phase space diagram to the one required for the multiturn injection, and momentum matching section where the dispersion parameters are matched to the required values (η_h=1.61 m, η'_h=0.36) at the injection point of the ring. Injection system consists of C type magnet and a pair of electrostatic inflectors.

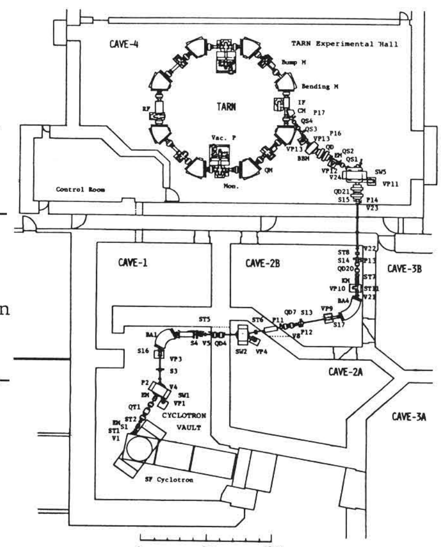

Fig. 2 Layout of TARN and beam transport system from SF Cyclotron.

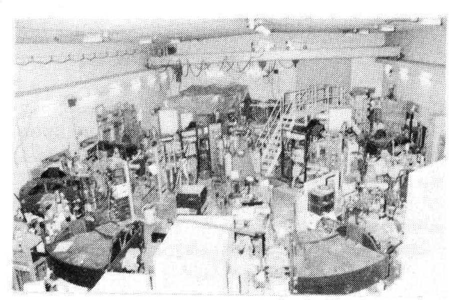

Fig. 3 Total view of TARN.

Obtained transmissions from the cyclotron to the ring are 17 % and 24 % for $\Delta p/p$ of 1/1500 and 1/1000, respectively. Measured emittances in mm·mrad are 15 for horizontal and 23 for vertical, and 12 and 16.5, after extraction from the cyclotron and in the third section of the transport system, respectively.

3. Vacuum.- Vacuum pressure lower than 1×10^{-10} Torr is required to achieve 90 % of survival probability for various ions accumulated during a period of 1 sec. Obtained pressure is 2×10^{-11} Torr by cooperation of turbomolecular pumps, sputter ion pumps and titanium sublimation pumps. A small pressure increase is found as the beam is being accumulated. This amount is less than 2×10^{-11} Torr for the injection current of 2×10^{10} particles/sec of He^{2+}. The most essential procedure is thermal baking applied during pumping down process. Pumping down curve from atmospheric pressure is shown in Fig.4. It takes about 60 hours to reach to 1×10^{-10} Torr and 150 hours to 3×10^{-11} Torr.

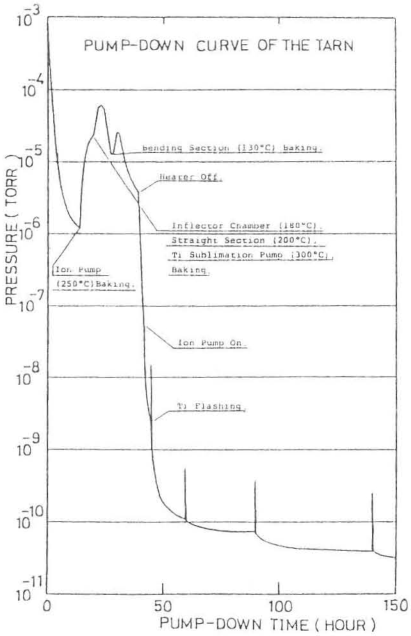

Fig. 4 Pumping down curve.

4. Multiturn Injection.- A combination of multiturn injection and RF stacking is applied to the TARN. Two pulse magnets are located upstream and downstream from the injection point along the circular orbit of the ring, which produce a distortion of closed orbit for a duration of their excitation. As the pulse fields are decreasing linearly, the beam fills up the transverse phase space of the ring. Only for multiturn injection, the maximum effective intensity corresponding to 34 turns was obtained. The injection of effective intensity of 20 turns into an optimum phase space considering the combination with RF stacking has been established. Figure 5 shows a typical result of this case using He^{2+} beam. The upper pattern shows the time structure of the current of a kicker magnet installed in the 2nd section of the transport system for shaping the beam to a duration of 80 μs, the middle shows of the pulse magnets for distorting the orbit and the lower shows the intensity increase of the 20 turn injection. The number of injected particles is estimated at 2×10^{8}. From the observation of injected beam profile, measured radial width is about 35 mm and then the emittance is 153 mm·mrad. The decaying curve of the lower pattern does not indicate intensity decrease, but debunching effect due to a momentum spread, because of a frequency dependence of an electrostatic beam monitor.

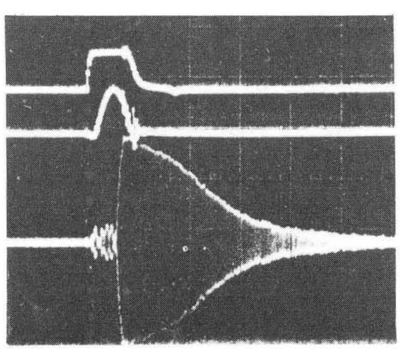

Fig. 5 Time structure of electrostatic monitor signal for the beam of 20 turn injection, upper and middle patterns show the current shapes of kicker magnet for beam pulsing and of pulse bump magnets for orbit distortion: 100μs/div.

5. RF Stacking.- A procedure of RF stacking is similar to the one which is used for the proton storage at ISR. CERN.[3] The RF voltage at capture process of injected beam with multiturn is determined as enough that its separatrix covers the longitudinal phase space area (∿1 rad·keV) of the beam. Then the RF voltage both in the capture and acceleration processes is chosen at about 1 kV, and consequently the period of phase oscillation is about 1 ms. For a synchronous phase of 30°, the change rate of momentum, dp/pdt, for synchronous particle is designed at 1.5×10^{-2} ms^{-1} and fractional momentum variation from the injection orbit to the bottom of stacking region is about 4 %. Then it takes 2.5 ms to move to the bottom of the stacking region. Change of revolution frequency is 30 kHz and acceleration frequency difference is 230 kHz. Momentum difference between the stacked beams at the bottom and top of the stacked region is designed at 2.5 % and then the RF frequency must be changed by 150 kHz. In order to keep synchronous phase of 30°, the time derivative of the frequency is of 9 kHz/ms for the voltage reduced adiabatically to 100 V. The time required for deposit is 17 ms. The expected maximum stacking number into transverse and longitudinal phase spaces is about 2000 turns.[4]

The efficiency for capture and transport processes to the stacking region was measured. The injected ions are well captured and transported at higher voltage than 130 V, and the efficiency is estimated at about 70 %.

Figure 6 shows a typical result of the multiturn injection observed by a permalloy monitor of much larger time constant (∿3s) than the one of the electrostatic monitor of Fig.5. In this case, the beam debunched due to a momentum spread

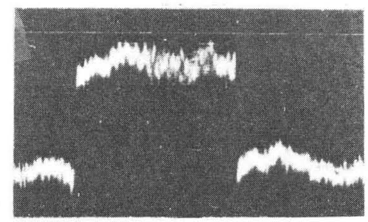

Fig. 6 Time Structure of the beam in multiturn, observed by permalloy monitor.

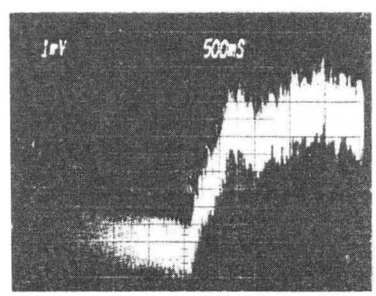

Fig. 7 Intensity increase by combination of multiturn and RF stacking (∿50 times).

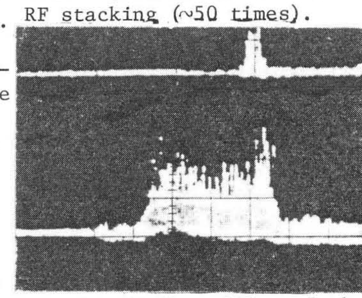

Fig. 8 Radial profiles of the beam by scintillation monitor. Upper: 20 turn injection, lower: combination of 20 turn injection and 10 time stacking. 2cm/div.

can be observed without decay. The rise of the beam signal indicates multiturn injection and fall indicates beam loss by exciting pulse magnets in the injection orbit for the next multiturn injection. The time duration of the beam existing in the injection orbit is 20 ms, which corresponds to the repetition of 50 Hz. By using this monitor, combination of multiturn injection and RF stacking were observed as shown in Fig. 7. In this case, stacking number was 50. It is well illustrated that the intensity is increasing as the stacking number.

Figure 8 shows another result of combination of multiturn and RF stacking. A radially movable scintillation rod monitor was used. Radial spreads due to emittance growth by multiturn and momentum growth by RF stacking are well illustrated. Upper pattern shows the radial beam profile of the 20 turn injection and lower pattern shows of 10 time stacking after the 20 turn injection. Total effective intensity is then of 200 turns, whereas number of revolutions may be 600, because multiturn and stacking efficiencies are 0.5 and 0.7, respectively. Number of the stacked particles is about 1×10^9. Fig. 9 shows intensity increases via numbers of stacking.

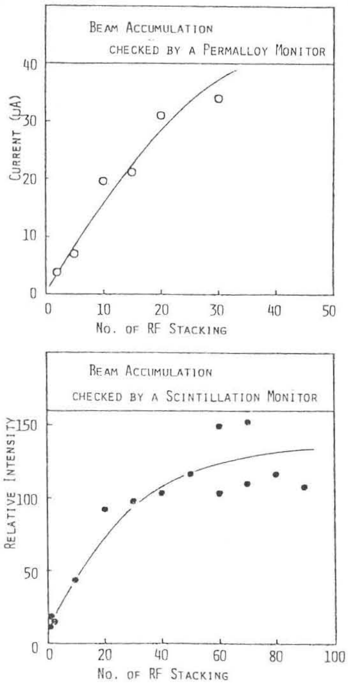

Fig. 9 Intensity increase via number of RF stacking.

6. Working Line Measurement.- In order to tune focusing elements in the ring, the working line was measured by an RF-knockout method. Measured ν-values are almost constant via momentum difference, and have a little difference with the calculated values by the computer program SYNCH. The chromaticity, $\xi = \Delta\nu/\Delta p/p$, is obtained to be $\xi_x = -1.59$ and $\xi_z = -0.47$ from these measurements. In order to control the chromaticity, two systems of 8 and 4 sextupole magnets were installed into the ring, although measurements by using these systems have not yet been done.

Due to the low velocity of the injected ions, the transverse collective instability is expected to play a major role in limiting the number of particles that can be accumulated. Without correction of the present chromaticity, this value is about 1×10^9. The number already obtained may reach to a critical region of stability. By using these sextupole system, the accumulated beam will be stable up to about 25 % (about 5×10^9) of the design value of this injection method (about 2×10^{10}). The incoherent space charge limit is the order of 10^{12} and much higher than those values.

7. Spectrum analysis of beam signals.- The harmonic amplitudes of beam signals from the electrostatic monitor were observed by a spectrum analyzer. A typical part of spectrum of bunched beam by multiturn injection is shown in Fig. 10a. At frequencies of 85.10 and 86.27 MHz, peaks are found, which correspond to the 72nd and 73rd harmonics of the revolution frequency of the beam. Similar observations were made for coasting beams, as shown in Fig. 10b. The observation was started 10 s after injection and continued for 200 s. The Schottky signal of coasting beam was observed.

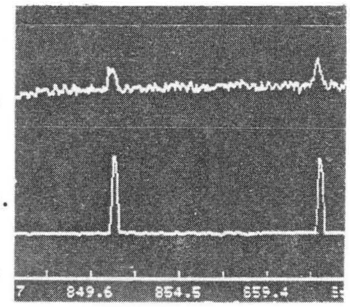

Fig. 10 Lower a) Spectrum of bunched beam by multiturn, peaks correspond to 85.10 (72nd) and 86.27 MHz (73rd). Upper b) Schottky signal of coasting beam.

Figure 11 shows the typical example of side bands, which are due to horizontal betatron oscillation, observed with electrostatic radial position monitor. From this result, the ν_x value is calculated at 2.245, which agrees well with one by the RF knock-out method (2.241). This method is very useful for ν value observation without destruction of beam.

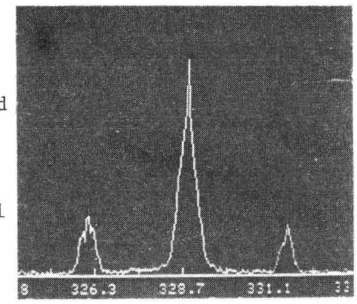

Fig. 11 Side bands due to horizontal betatron oscillation. Central peak corresponds to 32.88 MHz (28th), and side peaks appear at ± 278 kHz.

8. Life times of the accumulated ions. Lifetimes were measured for H^+, H_2^+ and He^{2+}. The molecular ion was chosen as the most fragile ion. Figure 12 shows an example of the observation for He^{2+} ions of 7 MeV/u by use of radially movable plastic scintillator probe. Beam profiles of 10,60, 180 and 300 sec after stacking processes are shown. Mean life of 250 sec is deduced from these results for the vacuum pressure (1×10^{-10} Torr) during these observations. The charge exchange cross section of 7 MeV/u He^{2+} is estimated at about 3×10^{-19} cm^2.

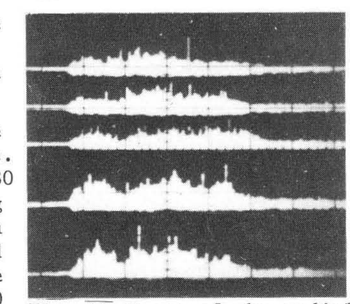

Fig. 12 Decay of the radial beam profile.

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