BEAM STACKING EXPERIMENTS AT TARN

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Abstract

TARN is a low energy (7 MeV/nucleon) ion storage ring aimed at the beam accumulation both in the longitudinal and transverse phase spaces from the injector cyclotron. It has been operated for this three years successfully and experimental results show the close agreement with the theoretical calculations. Twenty turns beam are stored in the betatron phase space area of 87 πmm·mrad by the multiturn injection method and 15 pulses are RF stacked in the momentum space $\Delta p/p$ of 2.2 %. Overall stacking number is then attained at around 300 turns. RF stacking is performed with the repetition rate of 30 Hz and it requires $\sim$ 0.5 sec to fulfill the whole phase spaces with the beam. Such performances of TARN are satisfactory for storing the beam from the injector cyclotron, and could justify the concept of installing the accumulation ring between injector and synchrotron for high current heavy ion acceleration.

1. Summary of Beam Stacking Experiments at TARN

A small ion storage ring, TARN has been constructed at INS for developing exclusively accelerator technology related to NUMATRON project. After the first success of beam injection in the TARN, July of 1979, we have made beam stacking experiments and have obtained the results which are in close agreement with theoretical calculations. They are summarized as follows.

a) Beams are transported from the cyclotron and are stacked in the betatron phase space of TARN by the amount of $\sim$ 20 turns.

b) They are debunched and adiabatically captured by the RF field and are moved to the top of stacking orbit which is 8 cm apart from the injection orbit. The capture efficiency is $\sim$ 70 % through this process.

c) RF stackings are performed with the repetition rate of 30 Hz and the beam intensity in the ring is increased linearly up to the RF stacking number of around 15. When stackings are performed more than $\sim$ 15 times, the stacking efficiency is decreased.

d) Profiles of multiturn injected and RF stacked beams are measured with destructive beam profile monitors. The betatron amplitude of multiturn injected beam is 17 mm at the centre of the straight section while the 20 times RF stacked beam occupy the spatial range of 5 cm. The momentum spread of RF stacked beam is estimated at 2.2 % which corresponds to $\sim$ 20 times larger than the momentum spread $\sim$ 0.1 % of injected beam.

e) Overall stacking number is a few hundred turns.

2. Procedure of Beam Stacking

Details of the ring can be found in the references.[1,2] however fundamental ideas of beam accumulation method are shortly described here. In Table 1 main parameters of TARN are listed.

Magnetic focusing system of the ring are eight bending magnets and sixteen quadrupole magnets with a lattice structure of FODO type. Additionally twelve sextupole magnets of two sets are installed for chromaticity corrections. The mean radius is 5.06 m while the bending radius of central orbit is 1.333 m. Eight straight sections, each of which is 1.80 m length, are served for various instruments of beam injection, stacking and beam diagnostic systems. Beams are transported from the cyclotron to the ring by the distance of $\sim$ 40 m and the momentum is analyzed to $\sim 1 \times 10^{-3}$

through the line. A kicker magnet located in the transport line, shapes the beam pulse width to ∿ 80 μsec suitable for multiturn injection. By the use of an electrostatic inflector and two bump magnets, beams are injected in the betatron phase spaces with the area of 103 πmm·mrad. Horizontal beam emittance at the injection point of the ring is assumed at 5 πmm·mrad and the net circulating current will be 18 turns. In this multiturn injection method, loss rate of the beam is calculated at 45 %.

Table 1 TARN Parameters

Max Beam Energy (ε = 0.3)	8 MeV/u
Max Magnetic Field	9.0 kG
Radius of Curvature	1.333 m
Average Radius	5.06 m
Useful Aperture	45 × 190 mm²
Revolution Frequency	1.3 MHz
Betatron ν Values (ν_x, ν_z)	2 ∿ 2.5
Transition γ	1.894
Injection Method	Multiturn
Momentum Spread of the Stacked Beam	2.46 %
Repetition Rate of RF Stacking	33 Hz
Vacuum Pressure	1×10^{-10} Torr
Space Charge Limit (N^{5+})	6×10^{10}

Multiturn injected beam is debunched at ∿ 250 μs after the injection due to its intrinsic momentum spread. Then the RF voltage is increased from zero to 77 V adiabatically in order to capture the coasting beam in the separatrix, of which the area is equal to the beam longitudinal phase space area, 100 keV·rad. In this capturing process, RF frequency is kept constant at 8.012 MHz, seven times the revolution frequency of particles on the injection orbit and hence the synchronous phase angle ϕ_s is 0 degrees. Period of phase oscillation is 0.45 ms at the end point of capture process and the period for increasing the voltage from zero to 77 Volt is chosen as 0.5 ms. Computer simulation shows that the rising period of nearly phase oscillation period can achieve the highest capture efficiency (∿ 80 %), whereas too shorter or longer period fail to trap the beam in the separatrix. In Fig.1 the functions of RF voltage and frequency are illustrated and parameters of RF stacking dynamics are given in Table 2. After the capture

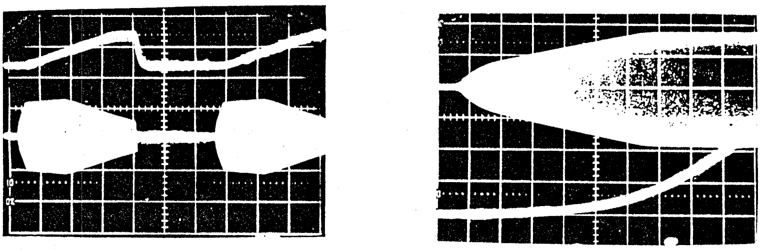

Fig. 1 RF frequency (top) and amplitude (bottom) modulations which are used for RF stacking. Horizontal scales are 5 ms/div (a) and 1 ms/div (b), respectively.

process (Region I), synchronous phase is increased from 0° to 15° (Region II), kept constant as 15° (Region III) and finally changed back to 0° (Region IV). Through the whole process, separatrix area is kept constant at 100 keV·rad in order to prevent the dilution of beam in the longitudinal phase space.

Table 2 RF Voltage and Frequency Parameters

Region	I	II	III	IV
Voltage V (Volt)	$0 \rightarrow 77$	$77 \rightarrow 224$	224	$224 \rightarrow 77$
Frequency Shift Δf (KHz)	0	13.7	166	120
Synchronous Phase ϕ (Degree)	0	$0 \rightarrow 15$	15	$15 \rightarrow 0$
Time Derivative of RF Frequency Shift $\Delta f/\Delta t$ (MHz/sec)	0	$0 \rightarrow 27.06$	27.06	$27.06 \rightarrow 0$
Period τ (ms)	0.5	1.0	6.0	8.8
Fractional Momentum Change $\Delta p/p$ (%)	0	0.24	3.21	5.35
Change of Closed Orbit ΔR (cm)	0	0.37	4.86	8.10
Fractional Frequency Change $\frac{\Delta f}{f}$ (%)	0	0.17	2.25	3.75

3. Experimental Data and Discussions

The RF stacking is repeated at 30 Hz and the beam intensity increases linearly up to the stack number of 15, while it shows the saturation at more stacking (Fig.2). From the experimental data of beam profiles (Fig.3), an amplitude of betatron oscillation x_β is measured at 17 mm and the emittance of the multiturn injected beam is deduced at 87 πmm·mrad, when the emittance of injected beam is 3.8 πmm·mrad. The momentum spread of the stacked beam can be estimated by measuring the spatial spread. Subtracting the injected beam width from the whole beam width, one gets 35 mm at the stacking number of 15. As the dispersion function is 1.6 m at the straight section, the resultant momentum spread is 2.2 %. The momentum spread of the injected beam is 0.1 % and the dilution factor in the longitudinal phase space is calculated at 1.5.

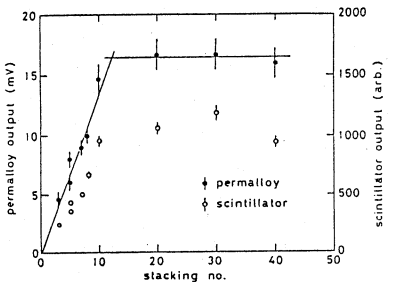

Fig.2 Intensity of stored current is measured with permalloy monitor and scintillation monitor. Intensity increases linearly up to the stacking number of 15.

As the preparatory work for stochastic beam cooling experiment, observation of Schottky signal was performed. Signals from an electrostatic pickup was fed to a

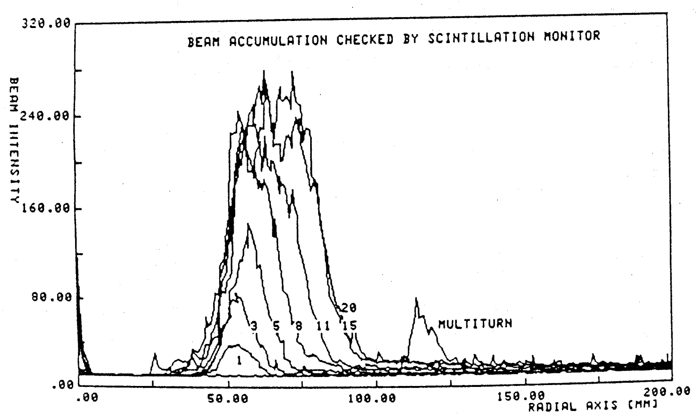

Fig.3 Beam profiles of RF stacked beam. Each number in the profile gives the number of RF stackings.

low noise preamplifier with a noise figure of 2.5 dB and the output signals are spectrum analyzed.

By use of the averaging function of spectrum analyzer with minicomputers, thermal noise current of preamplifier can be cancelled out. A typical example of the spectrum is shown in Fig.4 where the number of particle is around 10^8 and 2500 times averaging was performed. Each peak corresponds to the harmonic number of 72 and 73, respectively. When the signals of delta-type electrostatic pickup are analyzed, on-line tune values can be measured. Typical example of the spectrum is given in Fig.5 where the spacing of transverse and longitudinal modes Δf is 278 kHz. It is related with the fractional part of tune value q as

$$q = \Delta f / f_0 \ .$$

From the result, the ν-value at the injection orbit is calculated at 2.245, which is in close agreement with the value 2.241 obtained by an RF knock out method.[3)]

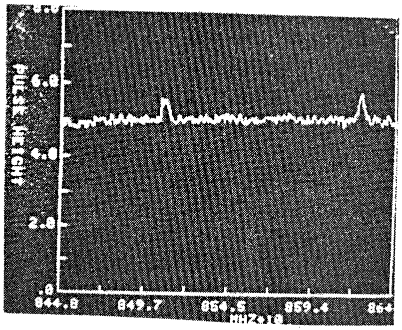

Fig. 4 Schottky signals observed at TARN. Two longitudinal signals corresponds to the harmonic number of 72 and 73, respectively. Signals are performed with 2500 times averaging.

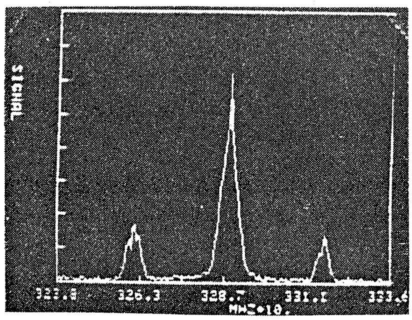

Fig. 5 Observed spectrum of a longitudinal and two transverse signals. The frequency spacing Δf between the transverse and longitudinal signals is 278 kHz, while the frequency of longitudinal one is 32.882 MHz (harmonic number 29).

4. Further Beam Experiments at TARN

Following beam experiments are scheduled and preparations are in progress.

a) Resonance crossing experiments

Integer, parametric and higher order resonances are crossed by sweeping the closed orbit with RF frequency modulation and by the sextupole magnets adjustment. Crossing speeds are arbitrary changed. Beam emittance growth associated with resonance crossing, is measured with beam profile measurement technique.

b) Beam transfer function measurement

The response of a beam to small transverse and longitudinal RF excitation is analyzed with Fast Fourier Transformer (FFT) which measures a spectrum nearly 100 times faster than the conventional spectrum analyzer. From the measured spectrum one can get a lot of informations about the beam distributions, wall impedances and also space charge impedances. Space charge impedance predominantly determines the stability conditions in the high current low energy rings and then the impedance measurements in the low energy rings such as TARN are important works.

c) Stochastic beam cooling

In TARN many pulses are RF stacked in the momentum phase spaces with its spread of 2 % or more and then stochastic momentum cooling is quite useful technique for obtaining the monochromatic heavy ion beams in the ring. Electronic systems with the band width of 100 MHz are prepared, by which the cooling time is expected to be $\sim$ 10 seconds. First trial is scheduled at the end of this year.

References

1) Y. Hirao et al., "Test Accumulation Ring for NUMATRON Project", IEEE. Trans. NS Vol. NS-26, No. 3 (1979)
2) T. Katayama, T. Nakanishi and S. Yamada, "Injection and Accumulation Method in the TARN", IEEE Trans. NS Vol. NS-28, No. 3 (1981)
3) A. Noda et al., "Characteristics of Magnetic Focusing and Chromaticity Correction System for TARN", ibid in reference 2).