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RF STACKING SYSTEM IN THE TARN

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TARN is a low energy (7.0 MeV/nucleon) heavy ion stacking ring in the longitudinal and transverse phase spaces. The RF system serves for stacking the heavy ion beam with a repetition rate of 40∿100 Hz. In this paper, the outline of low level RF electronics system and high power parts including the accelerating cavity are described as well as the experimental results of beam stacking. The RF system is phase-locked with bunched beam which is injected from the sector focusing cyclotron. The RF frequency is set to around 8.00 MHz and the sweep range of 350 kHz is enough for stacking a beam at the top of the stacked beam. The accelerating cavity is a ferrite-loaded one with a single gap and the RF power is fed into the cavity through a wide band transformer. In order to detect the phase and position of the bunched beam, two kinds of beam monitors such as current transformers of ferrite cores and electrostatic plates are used.

Introduction

A combination of multiturn injection and RF stacking was applied to the TARN.[1] In this injection method, heavy ions from the cyclotron were injected via a magnetic and an electrostatic inflectors while two bump magnets were excited, and then, stacked in a longitudinal phase space by an RF field. This injection scheme is very efficient for obtaining higher beam intensity.[2]

A procedure of the RF stacking in the TARN is similar to the one which is used for the stacking of high energy proton beam at ISR,[3] CERN.

The initial voltage of an RF field was determined to be such a value as the separatrix well cover the phase space area of the injected beam and is rather freely chosen within the limits of satisfying the above condition. Then the RF voltage at the capture process is chosen as the same value at the acceleration period, 1100 V, at which the period of phase oscillation is 1.13 msec.

The rate of change of momentum for the synchronous particle, $\frac{\Delta P/dt}{P}$, is designed at 1.52×10^{-2} (ms^{-1}) for the synchronous phase angle of 30° and RF voltage of 1100 V. The fractional momentum variation corresponding to the distance from the injection orbit to the bottom of the stacked region is 3.82 %. Then it is required 2.5 ms 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 as the harmonic number is seven.

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.

The final voltage is determined so that the area of the separatrix is just equal to or larger than the longitudinal phase space area of the injected beam, 0.88 rad·keV). Typical staking rate is 40 Hz and the final voltage is 100 V for this repetition rate. The RF voltage is reduced adiabatically and the necessary time to change from the initial bucket to the final one is designed as 6.3 ms.

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

The RF System

Low Level RF System

The RF system is composed of a low level RF electronics system and high power parts including an accelerating cavity, of which the diagram is shown in Fig.1. The low level RF electronics plays an important role to obtain phase lock mechanism between beam and RF accelerating field. It is used also to control the accelerating voltage and frequency so as to obtain the optimum RF stacking condition. Programmed accelerating voltage and frequency are illustrated in Fig.2.

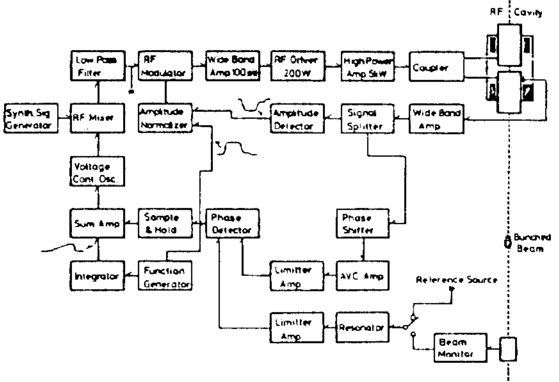

Fig.1 Block diagram of RF system

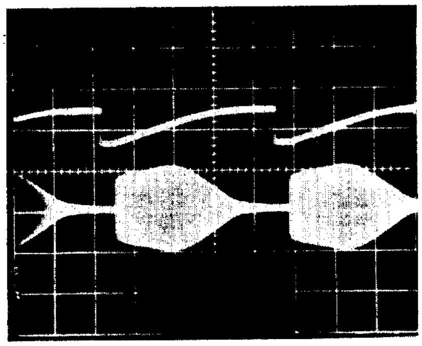

Fig.2 Accelerating voltage and frequency for RF stacking process, where the upper shows frequency change due to integration of voltage function and the lower shows accelerating voltage. Vertical scale; upper is 200 KHz/div, lower is 400 volt/div Horizontal scale; 2.5 ms/div.

The amplitude of RF field is modulated by a balanced modulator in accordance with the waveform from a function generator.

The amplitude control is performed in two functions, one is a negative feedback control and the other is a voltage compensation. In the negative feedback system, the envelope of RF signal from the

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accelerating cavity is fed to the amplitude normalizer which compares the input signal with the reference voltage coming from the function generator.

The open loop gain G_o of the feedback system is given by

$$G_o = G_t - G_n$$

where G_t is a total amplitude gain of the high power amplifier system and G_n is a total feedback gain of the system. They are adjusted at 17.3 dB, 57 dB and 39.7 dB, respectively. On the other hand the impedance of cavity is changed during the frequency sweep because the resonant frequency of the cavity is not swept. Then the RF voltage is inevitably changed due to the resonance property of the cavity which can be improved by the amplitude compensation system. Data of the measured resonant property of the cavity are stored in the central computer system, which calculates the compensated value and modifies the function voltage. With this system the amplitude can be compensated by the amount of 10 dB which corresponds to the frequency sweep of 350 kHz.

The RF voltage function generator is composed of DA converter with micro-computer system. The required function is calculated by minicomputer HP-1000 and the calculated results are transported to micro-computer. The micro-computer system has a control program area and a data loading memory area to store the function pattern. The stored data is selected by the control program and is sent to the DA converter. The data size is chosen as 512 byte per pattern block and then the resolution of voltage function generator is 1/256. The RF voltage is produced when a trigger pulse is applied to the function generator. The RF start timing pulse is synchronized with beam injection timing and is adjusted by digital delay circuit with the resolution of 100 nano second.

In order to move the injected beam to the stacking orbit the RF frequency should be decreased by the amount of around 350 kHz. During the process, the stable phase angle ϕ_s can be remained constant as the frequency change is proportional to the integration of RF voltage.

Phase locking between the bunched beam and the RF signal can be performed with phase lock loop in the system. The phase difference between the accelerating field and the fundamental mode of the bunch signal is measured by a phase detector, where the beam phase information is derived from a core-type or an electrostatic monitors.[4] The output signal of phase detector is fed to a voltage controlled oscillator (VCO) through a summing amplifier. The output frequency of VCO is determined by the voltage on a varacter, which is composed of a program term from the function generator and feedback one coming from the phase detector. The absolute value of the stable phase angle is determined by a phase shifter in the loop. In Fig.3 the beam signal from the electrostatic monitor (lower trace) with the RF signal of cavity (upper trace) in the PLL mode. At the measurement, injected peak beam current was around 15 μA.

In the phase lock mode, a lock-in time is decided by the closed loop gain and the transfer function of PLL, which are designed so as to minimize the phase-transient period in a lock-in process. The transient damping ratio is chosen as 0.8 to attain the phase-over-shoot less than 4.5° at the end of capture mode and the lock-in time is 130 μs.

High Power System

An accelerating structure is composed of two cavities with an electrical length of a quarter wave.

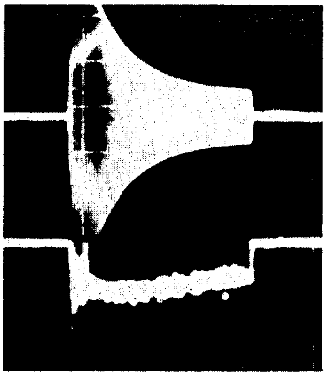

Fig.3 The beam signal from the electrostatic monitor (lower trace) and the RF field in the cavity in the PLL mode.

In order to tune the cavity over an operating frequency and to reduce the size of the cavity, 24 ferrite rings, 382 mm O.D., 260 mm I.D. and 20 mm thick, are stacked in the cavity. Each ferrite ring is sandwitched by water cooled copper discs. Electrical characteristics of several ferrite materials were investigated, and the ferrite with the highest μQf value was selected. The resonant frequency of the cavity is varied by changing a capacitance between two inner conductors or by impressing the biasing magnetic field in the ferrite cores. The two-turn bus bars are folded around the ferrite rings.

The RF power is fed to the cavity by a 5 kW RF power amplifier through a wide band transformer of a transmission type for the matching of their impedance. The transformer was also used to obtain two RF fields, whose phases are different by 180° from each other for the push-pull operation of the cavity.

The RF control system is supported by two mini-computer systems, HP-1000 and PANAFACOM-U400. The data logging and logical relay control are performed by U400 using the CAMAC interface system while the other interface of IEEE488 standard is also employed for the control of many RF components. Two computers are linked together and the stacking-program-execution is performed with use of two computer systems as well as the stacked data analysis.

RF Stacking Experiments

α particles were accelerated by the cyclotron to 28 MeV and were injected to TARN by the multi-turn injection method. The injected beam was, then, decelerated to the stacked orbit, inner part of the ring, by an RF field. A relation between RF frequency and the position of the equilibrium orbit was measured (Fig.4), where an experimental value of df/dx = 3.7 kHz/mm, is about 20 % smaller than the calculated value 4.45 kHz/mm from the formula

$$\frac{df}{dx} = \left(\frac{1}{\gamma^2} - \frac{1}{\gamma_t^{2}}\right) \frac{f}{\eta}$$

where f is the RF frequency, x the position, γ the Lorentz factor, γ_t the transition parameter and η the dispersion function.

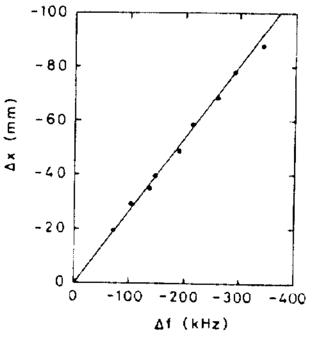

Fig.4 Position of the decelerated equilibrium orbit as a function of RF frequency.

The capture efficiency was also measured by use of the single rod monitor.[5] Figure 5 shows the observed beam intensity as a function of positions of decelerated equilibrium orbits. The sharp peak near the central orbit indicates the injected beam current. At an RF voltage of 130 V, the ions was hardly decelerated, whereas the ions was well captured and decelerated at higher voltages. By these measurements, the capture and deceleration efficiency is estimated at about 70 %.

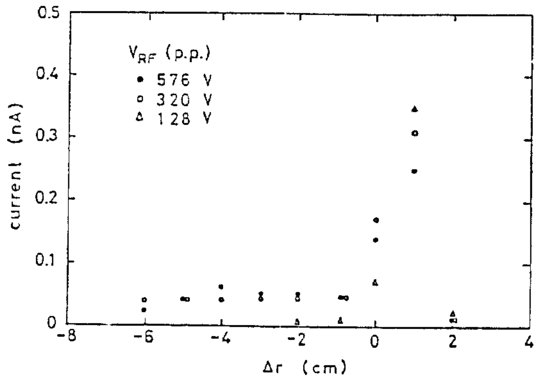

Fig.5 Measurements of RF-capture efficiency. The symbols Δ, and indicate the RF voltages of 130, 320 and 580 V, respectively.

At a fixed RF frequency, phase oscillations of ions in the synchrotron phase space were observed and is indicated in Fig.6 as a function of the RF voltage. A fit with theoretical prediction (indicated by the solid line) is fairly good.

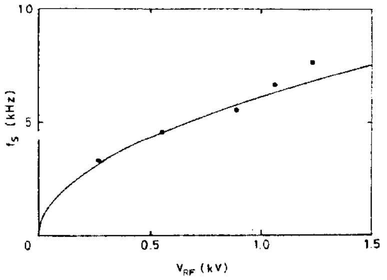

Fig.6 Observed frequency of the phase oscillation versus RF voltage

The stacked beam cannot be observed by the ESM, since the beam was debunched due to an intrinsic momentum spread. A movable plastic scintillator was used for measuring the beam profile after the RF stacking. Figure 7 shows an example of the RF stacked beam, of which the spatial distribution is around 8 cm.

An intensity gain of about 10 was obtained by applying the RF stacking method.

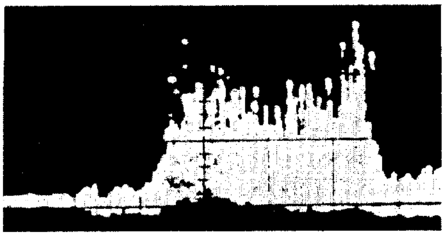

Fig.7 RF stacked α beam of 28 MeV. Spatial distribution is around 8 cm

Acknowledgements

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