

FIRST IDEA ON BUNCH TO BUCKET TRANSFER FOR FAIR

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Abstract

The FAIR facility makes use of the General Machine Timing (GMT) system and the Bunch phase Timing System (BuTiS) to realize the synchronization of two machines. In order to realize the bunch to bucket transfer, firstly, the source machine detunes slightly its RF frequency at its RF flattop. Secondly, the source and target machines exchange packets over the timing network shortly before the transfer and make use of the RF frequency-beat method to achieve the synchronization between two machines with accuracy better than 1°. The data of the packet includes RF frequency, timestamp of the zero-crossing point of the RF signal, harmonic number and bunch/bucket position. Finally, both machines have all information of each other and can calculate the coarse window and create announce signals for triggering kickers.

INTRODUCTION

The bunch to bucket transfer means that one bunch of particles, circulating inside the source machine, must be transferred in the center of a precise bucket and on the desired orbit of the target machine. It is realized by the General Machine Timing (GMT) system [1] and the Bunch phase Timing System (BuTiS) [2].

The main task of the GMT system is the time synchronization of more than 2000 Timing Receivers (TR) with nanosecond precision, distribution of timing events and subsequent generation of real-time actions by the TRs of the timing system located at the FAIR accelerator complex. The timing system is based on the White Rabbit (WR) network, which achieves the time synchronization by adjusting the clock phase (125 MHz carrier) and the time offset (Coordinated Universal Time – UTC) of all network TRs to that of a common grandmaster clock [3]. For the synchronization of radio-frequency (RF) components, the timing system is complemented and linked to the BuTiS. The BuTiS is a campus wide clock synchronization and distribution system. It generates an ident impulse clock at a rate of 10 μs, a 10 MHz sinewave reference clock and a 200 MHz sinewave clock [4].

After a bunch of particles is accelerated to the top energy, the RF flattop, it must be extracted from the source machine to be injected in the centre of a bucket of the target machine without phase and energy error, e.g. Four batches of U²⁸⁺, each batch has two bunches (h = 2), at 200 MeV/u of SIS18 will be injected into eight out of ten buckets of SIS100 [5] (see Fig. 1). This paper explains the process of the bunch to

bucket transfer. The first step is the frequency detune and the second step is the synchronization of two machines by the frequency-beat method.

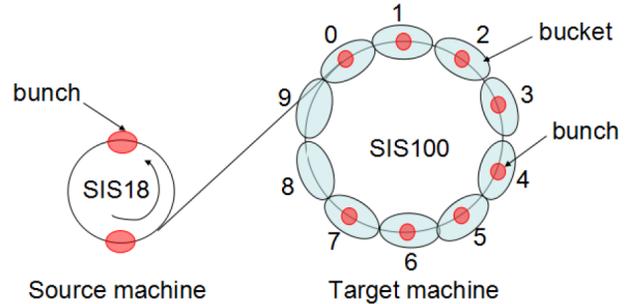


Figure 1: The bunch to bucket transfer of U²⁸⁺ from SIS18 to SIS100.

BEAM-DYNAMICS VIEW OF THE FREQUENCY DETUNE

The first step for the bunch to bucket transfer is the RF frequency detune. In order to realize the frequency-beat between two machines, the RF frequency of the source machine has to be detuned. It means that the particles run at an average radius different by ΔR from the designed orbit R. To make the frequency detuning effective, the feedback loop (i.e. the radial loop [6]) must be turned off just before the frequency detuning begins. Accepting to decenter the orbit by 8 mm for SIS18 [7]:

$$\frac{\Delta R}{R} \approx 2.4 \times 10^{-4}, \quad (1)$$

the RF frequency detuning at the U²⁸⁺ 200 MeV/u [7] extraction energy (γ = 1.217) is

$$\frac{\Delta f}{f} = -\frac{\gamma^2 - \gamma_t^2}{\gamma^2} \frac{\Delta R}{R} \approx 5 \times 10^{-3}, \quad (2)$$

where Δf is the frequency deviation for the frequency detuning, f is the RF frequency, γ_t = 5.8. The maximum RF frequency detuning is approximate to 7.5 kHz at 1.57 MHz for the U²⁸⁺.

The relative momentum shift is

$$\frac{\Delta p}{p} = \gamma_t^2 \times \frac{\Delta R}{R} \approx 8 \times 10^{-3}, \quad (3)$$

where p is the desired momentum of particle, Δp is the momentum shift caused by the frequency detune.

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The frequency detune process must be performed adiabatically. In order to perform this process adiabatically, the RF frequency detuning must be slowly enough for the longitudinal emittance to be preserved. The SIS18 synchrotron frequency Ω_s for the U²⁸⁺ is:

$$\Omega_s^2 \approx 13.35 \times 10^{-6}. \quad (4)$$

The SIS18 synchrotron tune Q_s at the RF flattop is:

$$Q_s \approx 0.00075. \quad (5)$$

During the frequency detuning process, the SIS18 synchrotron frequency must satisfy the following relation [6]:

$$\frac{1}{\Omega_s^2(t)} \left| \frac{d\Omega_s(t)}{dt} \right| \ll 1. \quad (6)$$

However, the frequency detuning will cause the average radial excursion and relative momentum shift.

SYNCHRONIZATION OF TWO MACHINES

The second step for the bunch to bucket transfer is the synchronization of two machines using the frequency-beat method. For each machine, the TR of the timing system is coupled to its RF system. After receiving the timing event (e.g. "Synchronization begin") from the timing network, the TRs enable to timestamp the zero-crossing point of the RF signals locally with accuracy better than 1ns. Besides, the TR at the target machine measures the phase of the harmonic number first (h=1) of the RF signal, with which the source machine can create the announce signals locally. Then the TR of the target machine sends the packet to the source machine. The data of the packet includes the RF frequency, timestamp of the zero-crossing point, harmonic number and the phase of h=1. At the same time, the source machine sends the packet to the target machine, which includes the same information but the phase of h=1. Both machines have all information so that they are able to calculate the propagation of uncertainties of the zero-crossing point measurement, the coarse window. Within this window, the bunch of particles could be transferred to the target machine with a deviation less than 1°. The source machine makes use of the information of the phase of h=1 to produce a series of announce signals to choose its next RF rising edges, which coincides with h=1 of the target machine. With the help of the coarse window and the announce signals, both machines can trigger their kickers.

Frequency-beat Method

Here we assume that the source machine is SIS18 and the target machine is SIS100. The SIS18 RF frequency is f_{rf}^{SIS18} and the SIS100 RF frequency is f_{rf}^{SIS100} . Δf is the RF frequency detuning value of the SIS18.

The number of SIS100 revolution to realize the synchronization is n.

$$n = \frac{t_{100best} - t_{18best} - \frac{\Delta n}{f_{rf}^{SIS18} + \Delta f}}{\frac{1}{f_{rf}^{SIS18} + \Delta f} - \frac{1}{f_{rf}^{SIS100}}} \quad (7)$$

t_{syn} is the time cost for the synchronization.

$$t_{syn} = \frac{(f_{rf}^{SIS18} + \Delta f) \times t_{18best} - f_{rf}^{SIS100} \times t_{100best} + \Delta n}{(f_{rf}^{SIS18} + \Delta f) - f_{rf}^{SIS100}} \quad (8)$$

where t_{18best} and $t_{100best}$ are the timestamps of the zero-crossing point of the RF signals measured by TRs with uncertainty [8] of 1 ns ($\delta t = 1ns$). Δn equals 1 when $t_{18best} < t_{100best}$ and equals 0 when $t_{18best} \geq t_{100best}$.

Coarse Window and Example

The coarse window is the result of the propagation of uncertainties of the zero-crossing point measurement.

$$A = \frac{(f_{rf}^{SIS100})^2 + (f_{rf}^{SIS18} + \Delta f)^2}{\Delta f^2}$$

$$B = \frac{2 \times [(f_{rf}^{SIS18} + \Delta f) \times (t_{18best} - t_{100best}) + \Delta n]^2}{\Delta f^4}$$

$$C = \frac{2 \times (f_{rf}^{SIS18} + \Delta f) \times (t_{18best} - t_{100best})^2}{\Delta f^3} + \frac{2 \times \Delta n \times (t_{18best} - t_{100best})}{\Delta f^3}$$

$$D = \frac{(t_{18best} - t_{100best})^2}{\Delta f^2}$$

$$\delta t_{syn} = (A \times \delta t^2 + B \times \delta f^2 - C \times \delta f^2 + D \times \delta f^2)^{\frac{1}{2}} \quad (9)$$

where we assume that $f_{rf}^{SIS18} = f_{rf}^{SIS100} = 1MHz$, $\Delta f = 100Hz$, $\delta t = 1ns$. Because the RF frequency has the long term stability, $\int \delta f dt = 0$.

Based on these assumptions, the coarse window is $\pm 14.143 \mu s$ of the best estimation. The maximum time for the synchronization is 10 ms. So the accuracy within this coarse window is better than 1°

$$\frac{10 \text{ ms}}{360^\circ} \approx 27.7 \mu s \quad (10)$$

Test Setup

We use two MODEL DS345 Synthesized Function Generators [9] with the frequency accuracy of ± 5 ppm of the selected frequency to simulate RF signals from RF cavities of SIS18 and SIS100. Two FPGA-based cards are responsible for the time/phase measurement, information transmission and coarse window calculation (see Fig. 2).

Test Result

This setup theoretically simulates the synchronization of two machines, with accuracy better than 1° (see Fig. 3). It paves the way for the further FAIR bunch to bucket transfer.

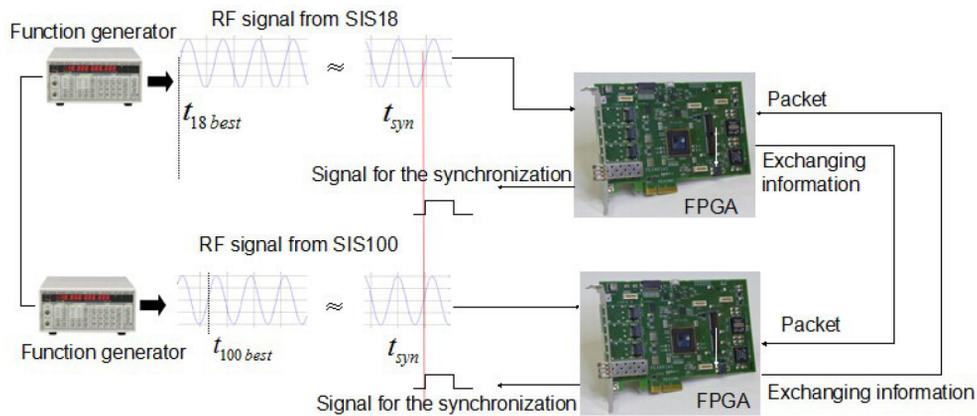


Figure 2: The test setup for the bunch to bucket transfer.

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The timestamp of RF signal from SIS18 (accuracy to 1ns)
Timestamp: 0x423c51cdc83
GMT: 1970-01-01 01:15:51.0.677369475

The timestamp of RF signal from SIS100 (accuracy to 1ns)
Timestamp: 0x423c51dcec5
GMT: 1970-01-01 01:15:51.0.677370053

The number of the revolution of SIS18: 5780
Synchronization time: 5.780000ms
Best estimation timestamp for the synchronization: 0x423c5750ea3
GMT for the synchronization: 1970-01-01 01:15:51.0.683149475

Uncertainty of the coarse window: 14.143µs

Period of synchronization is : 10000000ns = 10.000000ms
Current timestamp: 0x423c79bf0d8 (1ns)
GMT: 1970-01-01 01:15:51.0.719252184
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Figure 3: The test result of the bunch to bucket transfer.

SUMMARY AND IMPROVEMENT

This setup of the FAIR bunch to bucket transfer has been basically realized in the laboratory. It still has plenty of room for improvement. Improvements are:

- Compared with ± 1 ns uncertainty of the TR, the DSP system [10] from the department of Primary Beam RF at GSI reaches the uncertainty of $\pm 0.1^\circ$ of the measured phase, which corresponds to an accuracy of 50 ps of a RF frequency of 5.4 MHz. It will narrow the coarse window.
- The department of Primary Beam RF could provide RF signals of different harmonics of the target machine at the source machine instead of creating these signals locally, which is more precise and straightforward.
- The time consumption for the packet transfer over the current timing network is about 500 µs, which can be reduced to 200 µs without WR switches. We will connect TRs of two machines directly by the optical fiber.

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