The Synchronization for Bunch to Bucket Transfer at FAIR

J.Bai[1,2]* and O.Kester[1,2], R.Bär[1], D.Ondreka[1], T.Ferrand[1,3], M.Kreider[1], C.Prados[1], S.Rauch[1], W.Terpstra[1], and M.Zweig[1]

1. GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany

2. IAP, Goethe University Frankfurt am Main, 60439 Frankfurt am Main, Germany

3. TEMF, Technique University Darmstadt, 64291 Darmstadt, Germany

In case of a "bunch to bucket transfer" between two synchrotrons, after accelerating to the top energy, a bunch of particles will be extracted from the source synchrotron to be injected at the center of a RF bucket of the target synchrotron without the phase and energy error. For FAIR accelerator complex, the synchronization process is supported by the General Machine Timing (GMT) system [1] and the Bunch phase Timing System (BuTiS) [2]. The frequency beating method based on the RF frequency de-tune is adopted to realize this process. The RF frequency de-tune means that the particles run at an average radius different from the designed orbit, during which the energy keeps constant and the bending magnetic reacts. After the de-tune process, the relative RF phase of the two synchrotrons begins to slip at a repetition rate of the absolute value of the difference in two RF frequencies, which is the so-called frequency beating method. For the bunch to bucket transfer from the SIS18 to the SIS100, this method achieves the accuracy of the synchronization better than 0.5°.

PACS numbers: 29.20.D-. 29.27.Ac. 07.05.Dz

I. INTRODUCTION

The bunch to bucket transfer means that one bunch of particles, circulating inside the source synchrotron, must be transferred in the center of a precise RF bucket and on the desired orbit of the target synchrotron. It will be based on the General Machine Timing (GMT) system [1] and the Bunch phase Timing System (BuTiS) [2] in FAIR accelerator complex. 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 campus. 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 identical impulse clock at a rate of 10 μs, a 10 MHz sine wave reference clock and a 200 MHz sine wave clock [4].

After a bunch of particles is accelerated to the top energy, it must be extracted from the source synchrotron to be injected at, or at least be close to, the center of a bucket of the target synchrotron without the phase and energy error. e.g. From the SIS18, four batches[5] of the U^{28+} at 200 MeV/u, each of two bunches (h = 2), are injected into eight out of ten buckets of the SIS100[6] [10] (see Fig. 1).

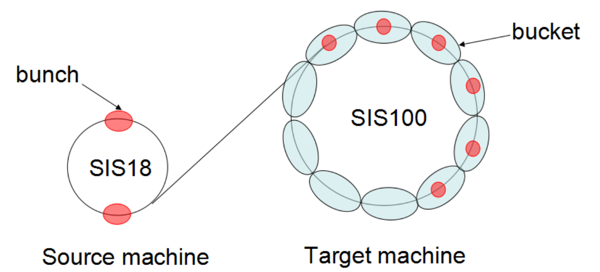

FIG. 1. The bunch to bucket transfer of U^{28+} from the SIS18 to the SIS100.

For properly transferring the beam from the source synchrotron to the target synchrotron, the phase between the beam and the bucket must be precisely controlled before it is ejected. The process of achieving the detailed phase adjustment is termed "synchronization". There are mainly two methods to realize the synchronization: the phase shift and the frequency beating, both of which are based on the RF frequency modulation. To achieve the a required phase shift, the RF frequency is modulated away from the a nominal value for a period of time and then modulated back. The frequency beating is an comparison between two RF signals of slightly different frequencies, perceived as periodic variations in phase difference [0, 2π] whose rate is the difference between the two frequencies.

We prefer to use the frequency beating method to realize the synchronization for the SIS18 and the SIS100, which has more synchronization chances compared with just once of the phase shift method. Fig. 2 shows the schematic of the synchronization process in one SIS18 cycle. A broad description of the synchronization process is as follows. On the RF ramp of the source synchrotron, the RF frequency de-tune is achieved. After receiving

* Email: J.bai@gsi.de

the timing event (e.g. "Synchronization begin") from the timing network, the TR which is coupled to the RF system then informs the RF device to collect information, including the RF frequency, the harmonic number, the phase difference between the RF signal and the reference signal and the timestamp of the zero crossing point of RF signal h = 1. After collection data, the RF device transfers data to the TR. Then the TR sends data to the TR of the SIS100 via the timing network. At the same time, the SIS100 does the same procedures. Until now, both synchrotrons have all information for the synchronization so that they are able to calculate the propagation of uncertainties [9] of the phase difference measurement, the coarse window. Besides, both synchrotrons resynchronize the RF signals of each other locally. With the help of the coarse window and the resynchronized RF signals, both synchrotrons trigger their kickers with precision better than 0.5°, which makes the RF frequency beating method possible.

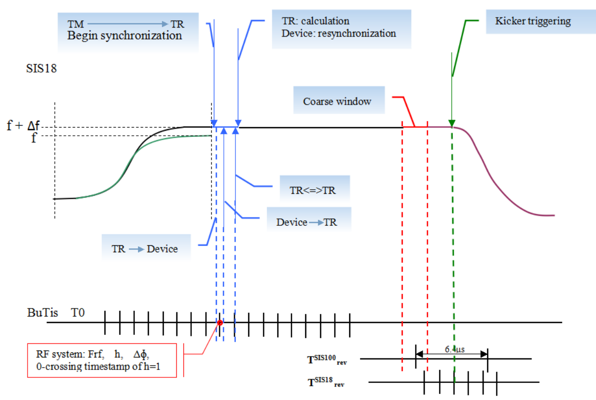

FIG. 2. The schematic of the synchronization process in one SIS18 cycle.

This paper, does not contain a detailed technical description of the synchronization process, rather is devoted to demonstrating the RF frequency de-tune from the viewpoint of beam dynamics and the theory of the frequency beating method instead, especially focusing on the bunch to bucket transfer from the SIS18 to the SIS100.

II. BEAM-DYNAMICS VIEW OF THE FREQUENCY DE-TUNE

The first step for the bunch to bucket transfer is the RF frequency de-tune. In order to realize the frequency beating between two synchrotrons, the RF frequency of the source synchrotron or the target synchrotron or both synchrotrons can be de-tuned. It means that the particles on the de-tuned synchrotron run at an average radius different by △R from the designed orbit R. For the synchronization of the SIS18 and the SIS100, we will de-tune the RF frequency on the SIS18. The SIS18 operates with a cycle length of 520ms, harmonic number of 2 (h = 2), and RF frequency of approximately 0.43 MHz at injection and approximately 1.57 MHz at ejection for the U^{28+} [10]. During nominal operation, the SIS18 forms two bunches from the beam injected at 11.4 MeV/μ and accelerates them up to 200 MeV/μ. From the SIS18, 4 batches, each of 2 bunches, are transferred at maximum 10ms intervals to the SIS100. The harmonic number of the SIS100 is 10 and the SIS100 RF frequency is fixed at approximately 1.57 MHz during the injection period to simplify the RF control system and to avoid perturbing batches already transferred.

This RF frequency de-tune is done accompanying with the RF ramp. Accepting to decentre the orbit by 8mm for the SIS18 [7]:

$$\frac{\triangle R}{R} \approx 2.4{\times}10^{-4} \tag{1}$$

We know the basic differential relations among the fractional change in the RF frequency f, the fractional change in the momentum p, the fractional change in the bending magnetic field B and the fractional change in the radius R as follows [8].

$$\frac{\Delta f}{f} = \frac{1}{\gamma^2}\frac{\Delta p}{p} - \frac{\Delta R}{R} \tag{2}$$

$$\frac{\Delta f}{f} = (\frac{1}{\gamma^2} - \frac{1}{\gamma_t^2})\frac{\Delta p}{p} + \frac{1}{\gamma_t^2}\frac{\Delta B}{B} \tag{3}$$

where γ is the relativistic factor, which measures the total particle energy, E, in units of the particle rest energy, E_0; γ_t is the transition gamma; $\triangle f$ and $\triangle B$ are the frequency and bending magnetic field deviation for the frequency de-tune; $\triangle p$ is the momentum deviation.

For J-PARC synchronizing the RCS (Rapid-Cycling Synchrotron) with the MR (Main Ring) or the MLF (Materials and Life Science Facility), the RF phase shift of the RCS is adopted [8]. To achieve a required phase shift, the RF frequency is modulated away from the required value for a period of time and then modulated back, when the extraction and injection energy match again. During its synchronization process, the magnetic field is not affected by the frequency change, namely ΔB = 0.

In our case of the frequency beating method, we guarantee the extraction and injection energy always match, which means that the momentum is not affected by the frequency change, namely Δp = 0; then the general relation between the radial excursion and RF frequency change Eq. (2) reduces to Eq. (4) and the general relation between the magnetic field change and RF frequency change Eq. (3) reduces to Eq. (5).

$$\frac{\Delta f}{f} = -\frac{\Delta R}{R} \tag{4}$$

$$\frac{\Delta f}{f} = \frac{1}{{\gamma_t}^2} \times \frac{\Delta B}{B} \tag{5}$$

From these equations, the RF frequency and the magnetic field change at the U^{28+} extraction energy 200MeV/u [7] ($\gamma_t = 5.8$) are

$$\frac{\Delta f}{f} = -2.4{\times}10^{-4} \tag{6}$$

$$\frac{\Delta B}{B} = -8.1{\times}10^{-3} \tag{7}$$

where the maximum RF frequency de-tune is approximate to 370 Hz at 1.57 MHz for the U^{28+}. In this paper, we assume Rf frequency de-tune for the SIS18 equals to 200 Hz for the sake of simplicity.

III. SYNCHRONIZATION OF TWO MACHINES

The second step for the bunch to bucket transfer is the synchronization of two synchrotrons using the frequency beating method. After the RF frequency de-tunes on the source synchrotron, the relative rf phase of the two synchrotrons begins to slip at a repetition rate of the absolute value of the difference in two RF frequency. When the correct amount of phase is accumulated, the bunch of the source synchrotron will align or be cogged with the bucket of the target synchrotron.

1. *The test setup*

Because the RF device is still under development, we use two MODEL DS345 Synthesized Function Generators [11] with the frequency accuracy of ± 5 ppm of the selected frequency to simulate RF signals from RF cavities of the SIS18 and the SIS100. Two TRs, the FPGA-based cards, are responsible for the time/phase measurement, information transmission and coarse window calculation. (see Fig. 3)

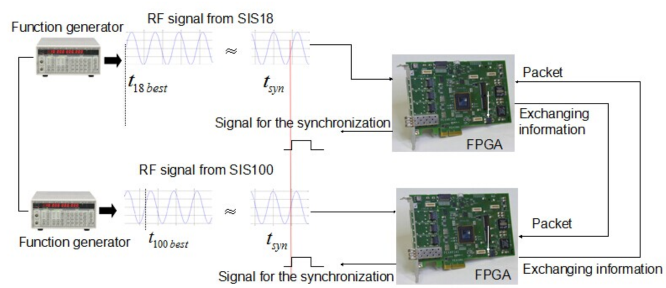

FIG. 3. The test setup for the bunch to bucket transfer.

2. *The frequency beating method*

Here we still assume that the source synchrotron is the SIS18 and the target synchrotron is the SIS100. The RF frequency of the SIS18 is denoted by f_{rf}^{SIS18} and that of the SIS100 by f_{rf}^{SIS100}. $\triangle f$ is the RF frequency de-tune value of the SIS18. n is the number of the SIS100 revolution period to realize the synchronization. t_{18best} and $t_{100best}$ are the timestamps of the zero-crossing point of the RF signals measured by the TRs. According to the measurement results, there are two scenarios.

- $t_{18best} < t_{100best}$

$$t_{100best} + n \times \frac{1}{f_{rf}^{SIS100}} = t_{18best} + (n+1) \times \frac{1}{(f_{rf}^{SIS18} + \triangle f)} \tag{8}$$

- $t_{18best} > t_{100best}$

$$t_{100best} + n \times \frac{1}{f_{rf}^{SIS100}} = t_{18best} + n \times \frac{1}{(f_{rf}^{SIS18} + \triangle f)} \tag{9}$$

Based on these two scenarios, we could deduce the formulas for the number of the SIS100 revolution n and the time t_{syn} spend on the synchronization.

$$n = \frac{t_{100best} - t_{18best} - \frac{\triangle n}{f_{rf}^{SIS18} + \triangle f}}{\frac{1}{f_{rf}^{SIS18} + \triangle f} - \frac{1}{f_{rf}^{SIS100}}} \tag{10}$$

$$t_{syn} = \frac{(f_{rf}^{SIS18} + \triangle f) \times t_{18best} - f_{rf}^{SIS100} \times t_{100best} + \triangle n}{(f_{rf}^{SIS18} + \triangle f) - f_{rf}^{SIS100}} \tag{11}$$

where $\triangle n$ equals 1 when $t_{18best} < t_{100best}$ and equals 0 when $t_{18best} > t_{100best}$.

3. *The coarse window and an example*

The coarse window is the result of the propagation of uncertainties of the phase difference measurements. The uncertainties in f_{rf}^{SIS18}, f_{rf}^{SIS100}, t_{18best} and $t_{100best}$ are independent and random, then the uncertainty [9] in the synchronization time t_{syn} is

$$\delta t_{syn} = \sqrt{(\frac{\partial t_{syn}}{\partial t_{18best}}\delta t_{18})^2 + (\frac{\partial t_{syn}}{\partial t_{100best}}\delta t_{100})^2 + (\frac{\partial t_{syn}}{\partial f_{rf}^{SIS18}}\delta f_{rf}^{SIS18})^2 + (\frac{\partial t_{syn}}{\partial f_{rf}^{SIS100}}\delta f_{rf}^{SIS100})^2} \tag{12}$$

After calculation, we get the result of δt_{syn}

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

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

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

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

$$\delta t_{syn} = (A \times \delta t^2 + B \times \delta f^2 - C \times \delta f^2 + D \times \delta f^2)^{\frac{1}{2}} \tag{13}$$

where we assume that f_{rf}^{SIS18}=$f_{rf}^{SIS100} = 1.57$ MHz, the RF frequency of the flattop of the SIS18 and of the injection of the SIS100 for the U^{28+}, $\triangle f$=200 Hz. In the real situation, the uncertainty of the phase difference measurement from the RF device is 50 ps, $\delta t_{18} = \delta t_{100} = \delta t = 50$ ps. Because the RF frequency has the long term stability in the real RF system, $\int \delta f_{rf}^{SIS18} dt = \int \delta f_{rf}^{SIS100} dt = 0$.

Based on these assumptions, the coarse window is $\pm 0.55\,[\mu\text{s}]$ of the best estimation. The maximum time for the synchronization is

$$\frac{1}{\Delta f} = \frac{1}{200Hz} = 5ms \tag{14}$$

Based on this window, we make use of the first SIS100 revolution signal after the t_{syn} - 0.55us and the following SIS18 revolution signal to trigger kickers. In order to guarantee that each bucket has opportunity to be injected, the whole period of the first SIS100 revolution signal is available. So the accuracy within this period is better than 0.5°

$$\frac{6.4\mu s}{5ms} \times 360^\circ \approx 0.46^\circ \tag{15}$$

Where 6.4 μs is the revolution period of the SIS100.

$$\frac{1}{f_{rf}^{SIS100}} \times h = \frac{1}{1.57MHz} \times 10 = 6.4\mu s \tag{16}$$

TABLE I. The test result of the bunch to bucket transfer

Bunch to Bucket Transfer of U^{28+} from SIS	18 to SIS100
SIS18 RF frequency (h = 2)	1.57 MHz
SIS100 RF frequency (h = 10)	1.57 MHz
The RF frequency de-tune of SIS18	200 Hz
The phase difference in the time domain	577 ns
The number of SIS100 revolution for the synchronization (n)	7112
The time consumption for the synchronization	4.530 ms
The synchronization period	5 ms
The coarse window	0.56 μs
The accuracy within one SIS100 revolution period	0.45°

4. Test result

This setup theoretically simulates the synchronization of two synchrotrons, with accuracy better than 0.5° (see Table I). It paves the way for the further FAIR bunch to bucket transfer.

IV. SUMMARY

The frequency beating method based on the RF frequency de-tune realizes the synchronization process between the SIS18 and the SIS100. It will be used for the synchronization of other machines for FAIR, such as the synchronization between the SIS18 and the ESR, the CR and the HESR and so on.

ACKNOWLEDGMENTS

The author would like to thank all staff in the department of control systems of GSI for their patient guidance, enthusiastic encouragement and useful critiques of the research work. The author would also like to thank staff from the Department Ring RF Systems to provide useful information about the RF system. The grateful thanks are also extended to Peter Moritz for his support.

Appendix A: The parameters related to the bunch to bucket transfer from the SIS18 to the SIS100

TABLE II. All parameters related to the bunch to bucket transfer for Radioactive Ion Beam (RIB) from the SIS18 to the SIS100

		RIB	
		SIS18 Extraction	SIS100 Injection
Designed Orbit	m	216.72	1083.6
Extraction kinetic energy	Mev/u	200	
Injection kinetic energy	Mev/u		200
RF harmonic		2	10 (2 bunch×4 batches)
RF frequency	MHz	1.572	1.572
RF period	μs	0.636	0.636
Revolution frequency	MHz	0.786	0.157
Revolution period	μs	1.272	6.359
β		0.568	0.568
γ		1.215	1.215
Transition energy γ_t		5.8	
Momentum compaction α_p		0.030	
ΔR/R		$\pm 2.4\times 10^{-4}$	
Max Δf/f		$\pm$0.024%	
Δp/p			1%
		Synchronization process	
Beating frequency	MHz	1.572+0.2	1.572
Frequency difference	Hz	200	
Synchronization period	μs	5	5
Δf/f by the frequency de-tune		0.013%	
Injection precison			better than 1^o

[1] D. Beck, et al., *THE NEW WHITE RABBIT BASED TIMING SYSTEM FOR THE FAIR FACILITY*, PCaPAC'12, India, p. 242, (2012)

[2] D. Beck, *Interface to BuTiS*, `https://www-acc.gsi.de/wiki/Timing/TimingSystemButisInterface`

[3] D. Beck, et al., *White Rabbit Technology as Basis for the FAIR Timing System* GSI Scientific Report 2011, p. 333, (2011)

[4] P. Moritz, *BuTiS - Development of a Bunchphase Timing System*, GSI Scientific Report 2006, p. 64, (2007)

[5] G. Dugan, *Considerations of BunchSpacing Options for Multi-Bunch Operation of the Tevatron Collider*, Fermi National Accelerator Laboratory, p. 1, (1989)

[6] D. Ondreka, *Settings Generation for the RF Systems in FAIR*, GSI/CERN Meeting 2014

[7] H. Liebermann, D. Ondreka, *FAIR and GSI Reference Cycles for SIS18*, GSI, October 3, 2013

[8] Eizi EZURA, Masahito YOSHII, *BEAM-DYNAMICS VIEW OF RF PHASE ADJUSTMENT FOR SYNCHRONIZING J-PARC RCS WITH MR*, High Energy Accelerator Research Organization, Japan, June, 2008

[9] John R. Taylor, *AN INTRODUCTION TO Error Analysis* University Science Books, Sausalito, California, 1997

[10] H Liebermann, D. Ondreka, *FAIR and GSI Reference Cycles for SIS18* Primary Beams - System Planning, Sausalito, GSI, 2013

[11] Stanford Research Systems, *MODEL DS345 Synthesized Function Generator*

[12] H. Klingbeil, *Low-Level-RF (LLRF) Systems for FAIR Synchrotron and Storage Ring Cavities*, FAIR-Technikforum, November.11.2010