SYSTEM DESIGN FOR A DETERMINISTIC BUNCH-TO-BUCKET TRANSFER*

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Abstract

A deterministic bunch to bucket transfer system is currently under development in the frame of the FAIR project at GSI. To achieve our accuracy and stability requirements, a set of hardware modules will be implemented. These hardware modules are expected to provide values such as the relative phase advance between the RF systems of both, the source and the target synchrotron according to an external timing system. These values are exchanged via optical fibers between different supply rooms, and the considered RF signals are re-synthesized locally. These re-synthesized signals are synchronized to enable a precise phase advance control between the synchrotrons' RF systems. The first step of the development consists in modeling the actual DDS and DSP-based LLRF environment of the SIS18 under Ptolemy-II. Measurements on real devices will be performed concurrently to the simulation. We expect to use this simulation to refine our timing expectations regarding the synchronization process and the inter-module communication protocols and design the synchronization function, which will be implemented on the hardware modules.

INTRODUCTION

As it is foreseen in the frame of the construction of the Facility for Antiproton and Ion Research (FAIR) at GSI Helmholtzzentrum für Schwerionenforschung GmbH [1], the existing SIS18 is used as a pre-accelerator for the new acceleration chain. To fulfill this task, a Bunch-to-Bucket transfer procedure is being investigated.

The SIS18 is a separated functions synchrotron designed to accelerate a variety of ions from protons to uranium with different mass over charge ratios. Two ferrite-loaded cavities in combination with three MA-loaded cavities bring the beam to the transfer flattop. The transfer is performed at harmonic number 2 (see Table 1).

Table 1: List of Beam Parameters for SIS18 at the Flattop for Uranium $^{238}\text{U}^{28+}$.

Parameters	Value
Bending field B_0	1.73 T
Magnetic Rigidity $B_0\rho_0$	18 Tm
RF frequency f_0	1.56 MHz
Circumference of the reference orbit L_0	216.72 m

The future SIS100 will have a maximum magnetic rigidity of 100 Tm for a reference orbit five times larger than the reference orbit of the SIS18. Injections will be performed on harmonic number 10, so that under the transfer conditions the relative bunch repartition in the SIS18 and in the SIS100 is periodical and its revolution frequency is the frequency of the SIS100 at harmonic number 1.

Independently from the applied method and from the conditions relative to the design of the different accelerators, which compose the acceleration chain, the procedure, which we refer to as synchronization consists in controlling the relative phase advance between RF signals of the SIS18 and the corresponding reference signals derived from the SIS100 RF system. The described synchronization procedure is required to ensure the capture of the bunches composing the beam extracted from the SIS18 by the RF field generated by the 14 ferrite-loaded cavities of the SIS100.

SYSTEM DESIGN

Beam Dynamics During the Synchronization

According to the circumference ratio of their reference orbits, the measured relative phase advance between corresponding RF signals of the SIS18 with respect to the SIS100 is constant. Modifying the bending field value at the transfer flattop in the SIS18 results in steering the beam on a so-called synchronization orbit, which introduces a linear variation of the relative phase advance between the corresponding RF signals of the SIS18 resp. the SIS100. According to the main synchronization scenario under development for FAIR the beam is extracted from its synchronization orbit, imposing a maximum relative radial steering during the synchronization procedure shown in Eq.1.

$$\frac{\Delta L}{L_0} = 2.4 \cdot 10^{-4} \qquad (1)$$

The energy matching between the two RF fields, is ensured for this maximum radial steering by modifying the bending field accordingly. The maximum frequency offset resulting from these modifications is $\Delta f = -360$ Hz.

The synchronization requirements are fulfilled periodically according to the beating frequency Δf. The transfer can be triggered within a transfer window defined by the maximum phase error expectation of $\pm\ 0.5°$

(SIS100, harmonic number 10). For an RF frequency offset of 360 Hz, the maximum beating period corresponding to a shift of the RF signal of SIS18 by one period on h = 2 lasts 2.8 ms. According to the location of the bunches, the beam can be kicked ± 3.86 μs around the optimal synchronization phase value [2].

Short Description of the LLRF Environment for FAIR

The LLRF environment developed for FAIR is based on a digital hardware implementation [3]. The RF driving signals are generated by Direct Digital Synthesis (DDS) modules operating in the range 0.1 to 27 MHz with a precision better than 2 Hz. A reference clock distribution system called BuTiS [4], composed of a sine-wave C_2 of frequency 200 MHz with a jitter in the range of some pico-seconds, and of a periodical synchronization pulse T_0 of frequency 100 kHz, is distributed over the campus at GSI and enables a coherent absolute time representation, shared across the LLRF layer. The phase advance is measured asynchronously on the basis of a CORDIC algorithm implemented on a Digital Signal Processing (DSP) module. Phase values are delivered every 3.22 μs with an uncertainty of 0.1° in the considered frequency range [5].

The communication on the LLRF layer is handled by point to point and token ring optical fiber protocols. The communication between different locations across the campus at GSI is taken in charge by the General Machine Timing (GMT) using the White Rabbit (WR) protocol. Data transfer through the Timing Network between different LLRF locations are delayed by at most 200 μs. The synchronization pulse T_0 is used to re-synchronize the transferred values.

The transfer scheme between the SIS18 and the SIS100 counts up to four consecutive transfers of two bunches each. The frequency beating scenario for FAIR is made possible by decentralizing the reference signals of each synchrotron based on one data transfer per cycle between the different LLRF locations. The data transfer is supported by the Timing Network. A precise phase measurement between the actual RF signal at the correct harmonic number at SIS18 and the corresponding decentralized RF Signal of SIS100 enables to calculate a synchronization window in which the extraction kickers can be triggered according to the bunch position. A symmetrical implementation at SIS100 enables to trigger the injection kickers. The filling of the SIS100 with multiple injections from the SIS18 is made possible by shifting the reference signal derived from the RF signal of the SIS100 at harmonic number 1 by 72° after each transfer.

Development of a Phase Extrapolation Topology

Due to asynchronous measurements, the phase value from the DSP module must be re-synchronized in order to be shared between different locations. Fig.1 presents the classical DSP-based phase measurement topology developed for FAIR. The reference DDS (DDS REF) generates locally a dedicated signal based on BuTiS, such that the frequency difference between this dedicated signal of frequency f_{REF} and the RF signal to be measured is smaller than 50 kHz.

$$f_{REF} = N \times 100\,\text{kHz} \qquad (2)$$

with

$$N = \text{round}\left(\frac{f_{RF}}{100\,\text{kHz}}\right) \qquad (3)$$

Considering this maximum frequency offset of 50 kHz, at least six phase advance samples are available per ramping period. An additional FIR filter enables to calculate dynamically the phase variation per sampling period.
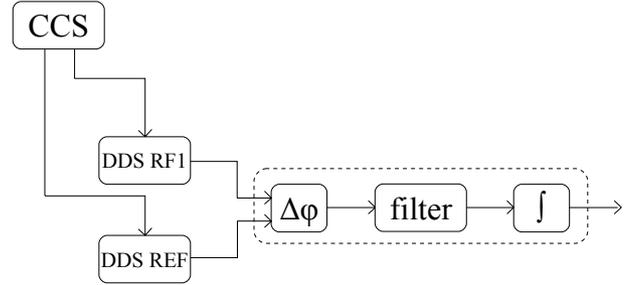

Figure 1: Topology of the DSP-based phase measurement.

At the beginning of the transfer flattop, a trigger signal is generated, which enables the phase acquisition. Under the assumption, that the frequency offset remains constant during this acquisition, an averaging of the phase variation is performed to reduce the influence of noise on the calculated value. Variations larger than 60° per sampling period, corresponding to phase jumps between +180° and -180° are treated specifically.

An external accumulator working on a 200 MHz clock makes use of the phase measurement and of the calculated phase variations to re-create the phase ramp. This makes possible to determine both, the absolute value φ and the corresponding slope $d\varphi/dt$ at a BuTiS T_0 pulse. As a conclusion the phase information is transferred into the BuTiS clock domain, and the pair $(\varphi, d\varphi/dt)$ can be sent as a telegram to the other synchrotron supply room without any loss of information.

Simulation

Simulation models have been developed for the frequency beating synchronization under Ptolemy-II [6]. DDS RF1 generates an RF signal of frequency 157 kHz (SIS100 at harmonic number 1). DDS REF generates a synchronous reference signal of frequency 200 kHz. The phase measurement is performed by a model of the DSP

system (see Fig. 1). The phase accumulation is performed at the rate 200 MHz. Fig. 2 shows the first results of simulation for the frequency beating method. The compared signals are the harmonic number 1 of SIS100 and the equivalent signal of SIS18. The shift of the reference signal simulates the synchronization of a decentralized reference signal derived from the SIS100 according to an extrapolated phase advance. A complete beating period between the two signals corresponds to five revolution periods of the beam in SIS18. Considering the synchronization between SIS18 and SIS100 independent from the bunch numbering in SIS18, the maximum phase advance correction before transfer on this signal is of 36° (360° at harmonic number 2 of SIS18).
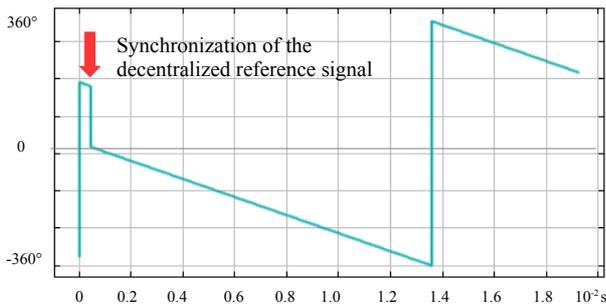

Fig. 2. Simulation of the frequency beating between the corresponding RF signals of SIS18 and SIS100 after introduction of the radial steering in SIS18.

Outlook

Further modules may be developed, which are expected to fulfill a variety of operations such as numbering the bunches or controling the synchronization in a closed-loop.

The main alternative to the frequency beating method consists in bringing the beam back on its reference orbit prior to the transfer, after a minimum beating period, using a so-called synchronization loop. Transferring the beam from the reference orbit in SIS18 may ensure the energy matching between the RF fields of SIS18 resp. SIS100. The maximum accepted energy drift during the synchronization procedure is given by Eq.4.

$$\frac{\Delta p}{p_0} = 8.0 \cdot 10^{-3} \qquad (4)$$

Assuming a constant bending field on the synchronization flattop this leads to a maximum frequency offset of 8 kHz (SIS18, harmonic number 2) and a maximum radial excursion of 8 mm. This method is submitted to an additional adiabatic criterion, indeed a sharp frequency ramping leads to bunch filamentation.

This criterion is fulfilled for slow frequency changes compared with the synchrotron frequency derivative during the RF manipulation. Dedicated simulations may help refining this criterion.

CONCLUSION

RF Control topologies have been successfully applied at GSI for a variety of operations [7,8]. This paper presents the guidelines for the development of a possible phase extrapolation function topology in the frame of the system design for a deterministic Bunch-to-Bucket transfer relying on the flexibility of functions based on DDS and DSP applications. Simulation based refinements regarding the existing Bunch-to-Bucket synchronization scheme and the phase shift alternative are being investigated.

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