PHASE CALIBRATION OF SYNCHROTRON RF SIGNALS*

A. Andreev†, H. Klingbeil[1], TU Darmstadt, Darmstadt, Germany
D. Lens, GSI, Darmstadt, Germany
[1]also at GSI, Darmstadt, Germany

Abstract

In the scope of FAIR's scientific program higher beam intensities will be achieved and several new synchrotrons (including storage rings) are being built [1]. The low-level radio frequency (LLRF) systems of FAIR have to support multi-harmonic operations, barrier bucket generation and bunch compression in order to meet the desired beam quality requirements. All this imposes several demands on the LLRF systems. For example the phase error of the gap voltage of a specific RF cavity must be less than ±3° [2]. Thus, each individual component must have a better accuracy. The RF reference signals for the FAIR synchrotron RF cavity systems are generated by direct digital synthesis (DDS). Four so-called Group DDS modules are mounted in one crate. In the supply rooms, the reference signals of such a crate are then distributed to local cavity LLRF systems [3]. Therefore, the precise phase calibration of Group DDS modules is of importance to prevent phase errors in LLRF signals of FAIR. A phase calibration method with respect to absolute phases of DDS modules defined by means of the FAIR Bunch Phase Timing System (BuTiS) is developed, and its precision is under evaluation.

INTRODUCTION

Due to the large circumference of the SIS100 synchrotron (1084 m) the RF reference signals are generated locally in four supply rooms distributed along the ring. These signals are generated by DDS modules fed with the same RF frequency ramp data provided by the Central Control System (CCS) (Fig. 1).

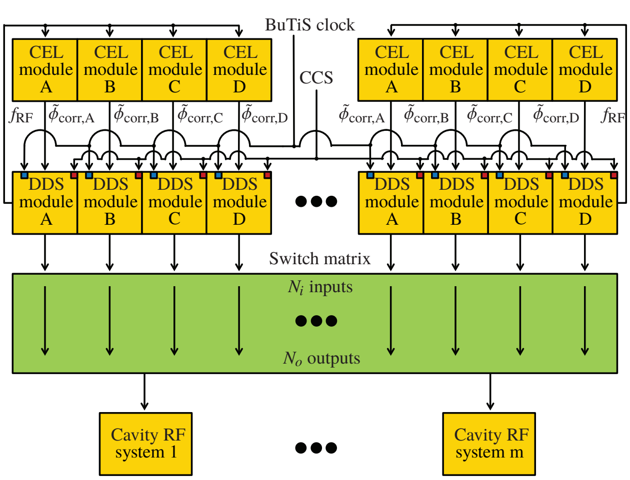

Figure 1: Routing of Group-DDS signals to cavity systems.

In each supply room there is at least one so-called Group-DDS module crate with four DDS modules mounted together, which allows to perform various multi-harmonic operations. Each DDS unit operates at a certain mode defined by the harmonic number h that is generally independent of the module and can be changed during the operation. The time synchronization of those Group-DDS units located in different supply rooms is done by means of a precision timing system called BuTiS (Bunch Phase Timing System) [4]. The signals generated by the Group-DDS units are then routed to the corresponding local cavity RF systems by means of a switch matrix with N_i inputs and N_o outputs.
Since the DDS modules generate reference RF signals for different LLRF systems, the precise calibration of units is of importance.

PHASE RESPONSE COMPENSATION

For the broadband frequency span during the whole acceleration cycle, all the DDS modules must remain in phase. However some hardware components of DDS modules such as a low pass filter and a balanced-to-unbalanced transformer show a frequency dependent phase response. Since the harmonic numbers of the DDS modules may be different, the phase response is not the same for all the modules, and a phase shift between different DDS RF signals occurs, i.e. the concept of in-phase multi-harmonic operation is disturbed.

Calibration with Respect to Higher Harmonic

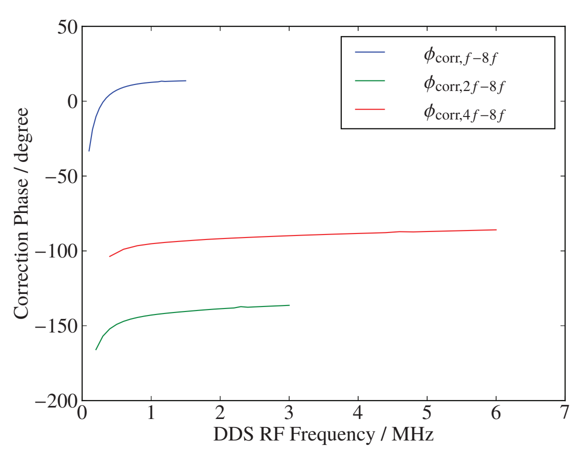

Figure 2: Results of the formerly used procedure.

The formerly used Group DDS calibration procedure [5] by means of Calibration Electronics Modules (CEL, [6]) was successfully validated by the results of a machine development experiment [7]. This calibration procedure uses the

* Work supported by GSI
† andreev@temf.tu-darmstadt.de

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DDS module configured to the highest harmonic number as a reference, and, hence, the calibration is done with respect to this module. Also during calibration, the harmonic number of each module is fixed. If the harmonic number of the DDS module is changed, then the calibration data stored in CEL modules are no longer valid and one has to repeat the process for the new h value. Therefore, a new calibration method with respect to absolute phases of DDS modules has been proposed and is being verified. With the proposed method the calibration data stored in CEL stays valid independent of the harmonic number realized by the DDS.

Absolute Phase Calibration

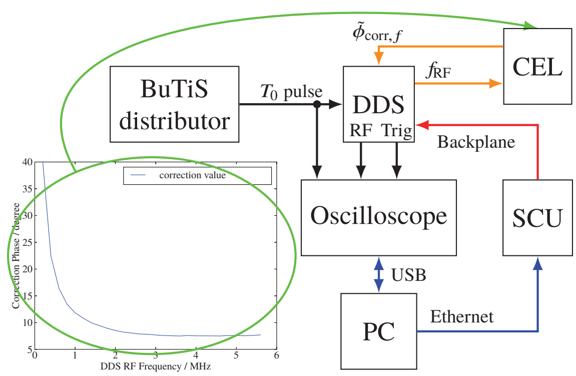

Figure 3: Measurement setup layout.

The BuTiS T_0 signal with a 10 μs period is used as one of the clock signals for DDS modules to ensure that reference RF signals generated by Group DDS modules are time synchronized [8]. Therefore the measurement procedure is synchronized with the T_0 pulse train in order to increase the accuracy of the DDS RF phase measurements. The measurement setup includes (Fig. 3):

- DDS module under calibration
- Scalable Control Unit (SCU) controlled by the PC[1] and forwarding data with the frequency tuning word to the corresponding modules via the backplane
- BuTiS reference signal generator and distributor

All the traces are measured by an oscilloscope and the acquired data are transferred into the PC which performs the subsequent analysis. The resulting phase correction data can finally be stored in a CEL module, which receives telegrams with the DDS frequency via optical fiber link and provides optical telegrams with phase corrections. For the calibration procedure a sequential trigger pattern of the oscilloscope is used. The first pre-condition to arm the oscilloscope is the output trigger signal of the DDS module, marking the moment when the new frequency tuning word is received by the DDS. The oscilloscope is triggered on one of the next periods of the T_0 pulse N_{T_0} and the DDS RF signal portion after the trigger is used for the subsequent analysis (Fig. 4).

[1] During regular operation the SCU receives the data from the CCS

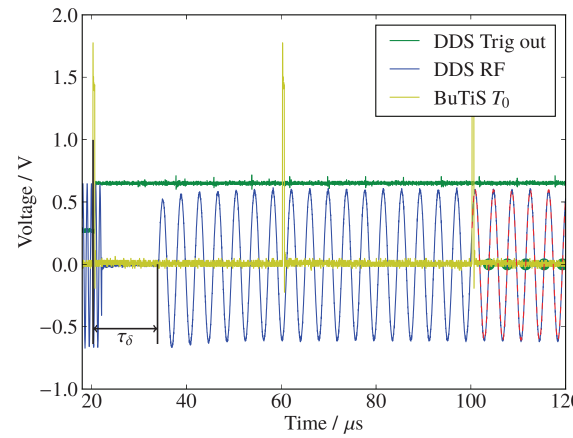

Figure 4: Trigger sequence.

The DDS RF output signal phase $\hat{\phi}_f$ is precisely estimated with a four-parameter sine wave fit algorithm [9] for each measurement. The phase correction value $\tilde{\phi}_{\mathrm{corr},f}$ for every frequency under calibration is obtained with

$$\phi_{\mathrm{corr},f} = \hat{\phi}_f - 2\pi f \left(N_{T_0} \times 10\mu s - \tau_\delta\right), \quad (1)$$

$$\tilde{\phi}_{\mathrm{corr},f} = \left[\left(\phi_{\mathrm{corr},f} + \pi\right) \bmod 2\pi\right] - \pi, \quad (2)$$

where τ_δ is the dead time of the DDS unit after a T_0 slope to realize the new frequency tuning word settings at the analog RF output, including the delays of digital processing, PCB, filters and cables. The resulting phase correction table (Fig. 5) can be stored into the CEL module and applied during regular operation. The standard deviation of the obtained phase is less than 0.2°, which allows to meet the desired phase accuracy requirements.

The measurement as well as the data analysis procedures are automatized by means of Python scripts allowing to perform calibration quickly and comfortably.

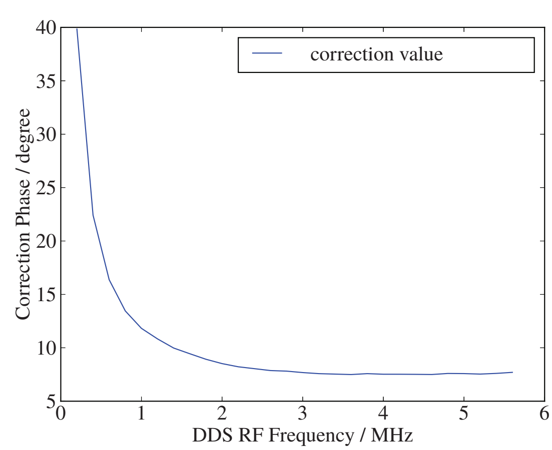

Figure 5: Example for a DDS module phase response measured with respect to BuTiS T_0 pulse.

MEASUREMENT RESULTS

Comparison with the Formerly Used Procedure

One of the possible validations of the proposed method is a comparison with the results of the formerly used procedure. The phase correction value of the calibration with respect to higher harmonics is obtained with:

$$\phi_{\text{corr},h_{\text{cal}}f} = \phi_{h_{\text{cal}}f} - \frac{h_{\text{cal}}}{h_{\text{ref}}}\phi_{h_{\text{ref}}f}, \tag{3}$$

where h_{cal} and h_{ref} are harmonic numbers of the module under calibration and the reference DDS module, respectively. For the comparison $h_{\text{cal}} = 1$ and $h_{\text{ref}} = 8$ were chosen and phase correction values with both procedures were calculated. The results obtained with respect to the T_0 pulse were then calculated with Eq. 3. The comparison between both methods is given in Fig. 6. The mean deviation between correction values is in the range between 3 and 5 degrees. We are still analyzing the cause for this difference. Nevertheless it can be seen that the calibration with respect to absolute phases of the DDS modules shows a good agreement with the results of the formerly used procedure and both methods lead to consistent results.

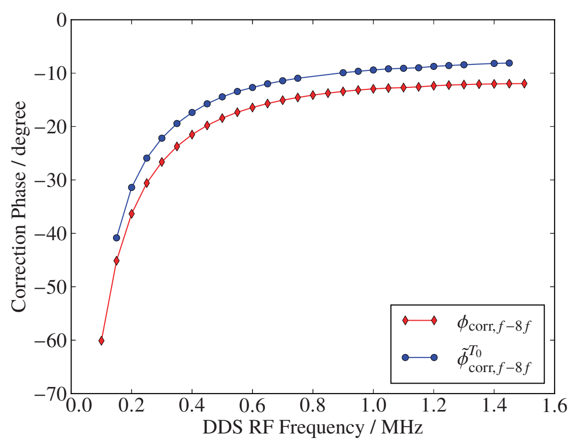

Figure 6: Comparison with the formerly used procedure.

OUTLOOK

The next step and ultimate proof for the proposed method will be an experiment emulating multi-harmonic operation of several DDS modules. For this purpose phase correction data at $h = 1$ for several Group DDS modules can be measured and loaded into corresponding CEL modules. The remaining phase shift between RF signals generated by these modules operating at different harmonic numbers is expected to fulfill requirements of multi-harmonic operation.

CONCLUSION

A phase calibration method with respect to the absolute phases of DDS modules has been developed, allowing to use the same calibration data for the DDS modules operating at different harmonics. The standard deviation of the obtained phases doesn't exceed 0.2°, allowing to meet the desired phase accuracy requirements. The results of the proposed method show a good agreement with the results of the formerly used procedure.

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