

GENERATION OF RF FREQUENCY AND PHASE REFERENCES ON THE FAIR SITE

B. Zipfel, U. Laier, K.-P. Ningel, S. Schäfer, C. Thielmann, GSI, Darmstadt, Germany
 U. Hartel, TEMF, TU Darmstadt, Germany
 D. Lens, IAT, TU Darmstadt, Germany
 H. Klingbeil, TEMF, TU Darmstadt; GSI, Darmstadt, Germany

Abstract

Based on the Time Synchronization System (BuTiS) [1] local analogue radio frequency reference signals (RF references) like the particle revolution frequency and their multiple harmonics will be generated. These references are used to control the phase of the accelerator cavities at altering harmonics of the bunch revolution frequency.

Delays or phase shifts from the FAIR-Centre to the references at the BuTiS endpoints are already compensated by the BuTiS receivers. Phase shifts from the RF reference generators to LLRF electronics can be compensated by controlling the output phases of the DDS modules of the RF references. However, phase shift delays of multiple harmonics at the same interconnecting electrical path are not identical at the same time. Configurable electronics [2] manage phase calibration of the RF references to their endpoints. In most cases, the calibration depends on the frequency and the harmonic number of the RF reference, as well as on thermal effects. The electrical length and impedance mismatches of interconnecting cables for phase control loops can be compensated. This is an important feature, in particular if control loops are switched between different harmonic frequencies.

CHALLENGE & REQUIREMENTS

For RF synchronization purposes in SIS18 (dual harmonic operation requirements) for phase stability exist: within a frequency range of 0.4-5.4MHz a maximum phase error of $\Delta\phi_{rf} < 1^\circ$ is tolerable. This leads to an overall signal distribution path variety smaller than $\Delta L/L < 1/1000$ and implies for a signal cable length of $L=100m$ a stable electrical delay of smaller than 500ps.

As an example, we compare this specification with the thermal expansion of copper wire. Assuming a coefficient of thermal expansion of $\alpha_L > 15 \times 10^{-6} K^{-1}$ and a temperature difference of $\Delta T=40^\circ C$, a signal path length variation of $\Delta L \sim 6cm$ is estimated. Thermal drifts of signal distribution amplifiers are another source for phase variations.

Phase detection depends also on the different nonlinear delay functions of the interconnection signal path lines. In practice, distribution amplifiers and cable impedance cannot be neglected (Fig. 1). Signal $f(t)$ could be the bunched beam signal (from Fast Current Transformer FCT, or Pick-Up) or the sinusoidal gap monitor signal. The signal delay from measurement point to synchronization system is in the order of $0.5\mu s$. Signal f_0 is the frequency and phase reference signal; its signal

delay could be much smaller than $0.5\mu s$. The signal delays $\Delta\tau$ have different characteristics depending on length L , frequency f , temperature T and time t (e.g. aging effects). If these characteristics are known, they can be superposed to the reference signal. As a desired result, the precision of the phase detection increases.

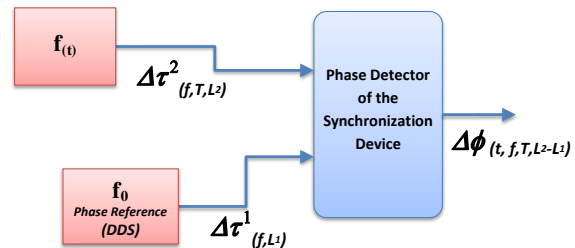


Figure 1: Influence of signal line characteristics on the phase detection of the synchronization system.

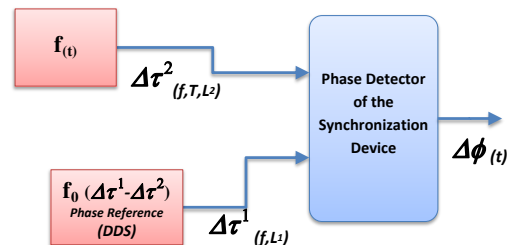


Figure 2: Signal phase detection with compensation of interconnecting cables by a numerically controlled DDS

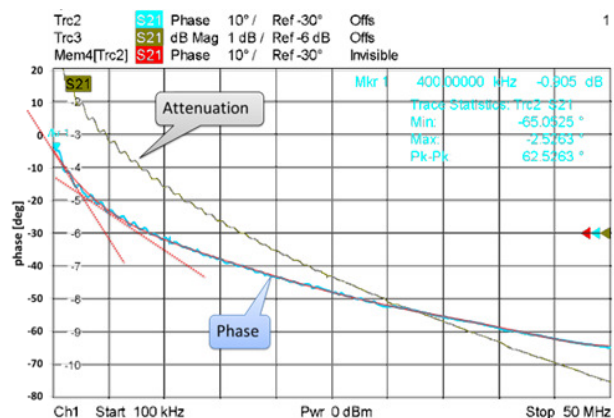


Figure 3: Nonlinear phase behaviour of 100m signal line RG58 measured with a Network Analyser.

As an example the electrical delay of 100 meters RG58 varies with respect to the SIS18 harmonics up to 5ns (e.g.

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using Andrew HELIAX cable the effect would be smaller but not negligible). The frequency ranges of harmonic numbers 1 and 8 in SIS18 lead to different electrical delays indicated with straight red lines (Fig. 3).

A straightforward way to fix this difficulty is to select phase and temperature compensated cables carefully and lengthening both signal paths exactly to the same electrical delay. A more elegant and a much cheaper solution is to add a characteristic function to the numerically controlled oscillator in such a way that the resulting phase difference will be compensated.

CONFIGURATION

Whereas a phase rotator could compensate constant delays, nonlinear effects have to be compensated by a multi-dimensional look-up table (LUT) in order to fit special characteristic curves.

The characteristic curves are determined at the endpoint of the two signal lines with a digital oscilloscope (DSO). For some frequencies, the phase difference is measured. The precise phases are derived from a least squares optimisation fit of the digitized waveforms. To enhance precision of the signal phase determination the optimisation can be done with respect to the zero crossing of the signal or with respect to the fundamental of the signal, depending on the application with clock signals or to match with small bandwidth applications. Finally the smooth characteristic curves are generated by a piecewise polynomial interpolation of the measurement points.

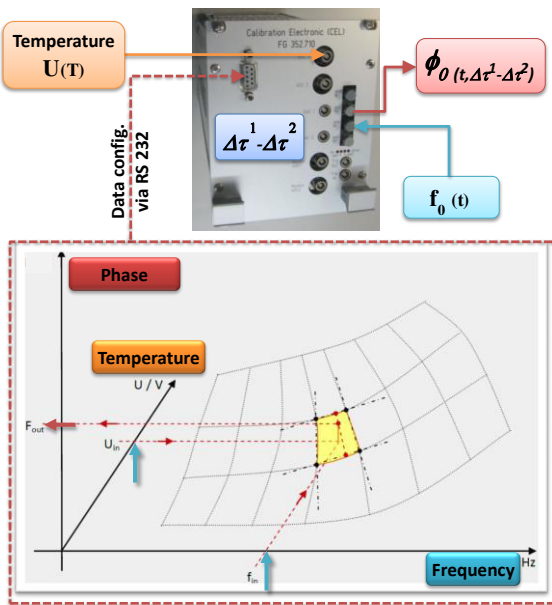


Figure 4: CEL configuration to calibrate DDS phase.

An automatic acquisition process and signal analysis with MATLAB scripts were developed to acquire curves quickly and more comfortably. In order to get rid of the aging problem, during periodic test cycles calibration curves could be updated automatically using the 'GSI M&D' firmware administration system [3].

For the SIS18 RF reference generation the currently available FPGA-based Calibration Electronics (CEL) [2] can be used for fast control (100 kHz bandwidth) of the phase output of the DDS module. For a proof of principle one CEL module is used to control a dedicated DDS module. The digital optical input at the CEL module is used to read in the momentary bunch revolution frequency and the analogue input could be used optionally for the temperature measurement (Fig. 4).

In addition to the phase shift of the signal lines, the anti-alias filters and the output transformer of the 'Group-DDS' hardware cause a nonlinear phase response especially in the low frequency range. For this reason the relatively large correction values of the 'Group-DDS' output were no surprise.

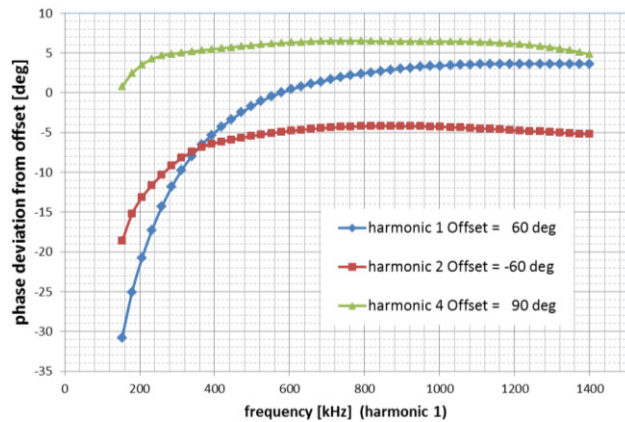


Figure 5: Phase correction functions for DDS reference generation with respect to the harmonic number h=8.

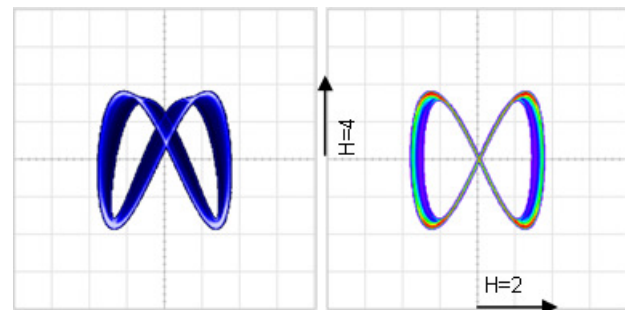


Figure 6: Verification of phase between harmonics before (left) and after (right) numerical phase output correction.

Even though the hardware of the 'Group DDS' was developed for a dedicated bandwidth from 0.8-30MHz, it was possible to extend its lower frequency limit by about 4 harmonic numbers to 0.2MHz and use the existing hardware for the revolution frequency (h=1) reference.

EXPERIMENTAL VALIDATION

To prove the correction of the phase references, the cavity synchronization system of SIS18 has been validated by a machine experiment. The beam ($^{58}\text{Ni}^{26+}$) was bunched with harmonic number h=4 and re-bunched with h=8 after injection and also before extraction. The

first cavity was running on harmonic $h=4$ and had accelerated the beam. The second cavity, positioned opposite in the SIS18, was running with $h=8$. The phase of the two cavities could be verified with respect to the bunch signal (Fig. 7). The bunch signal was recorded with an FCT.

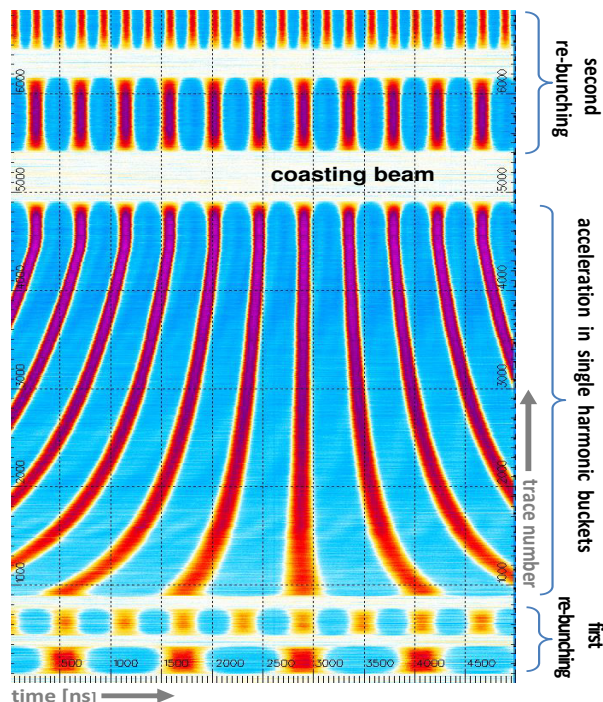


Figure 7: FCT signal of the machine cycle to verify two reference DDS ($h=4$ and $h=8$) on 2 different frequencies.

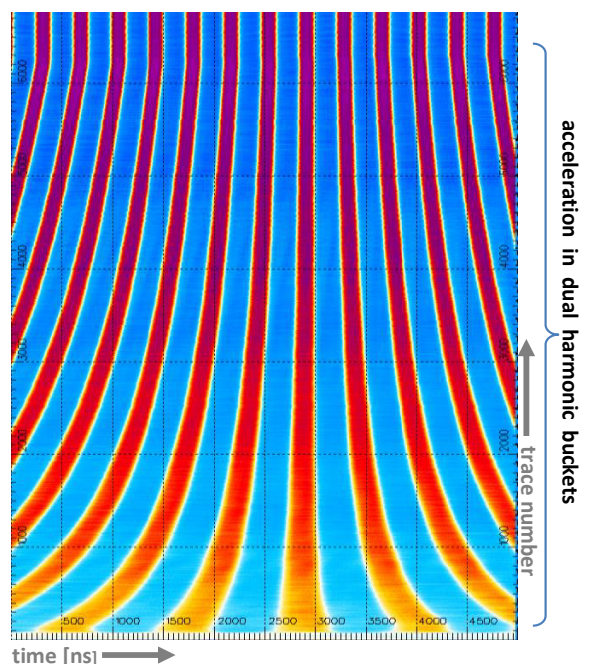


Figure 8: FCT signal from dual harmonic acceleration machine cycle to verify reference DDS.

The ultimate proof of the synchronization system calibration is the acceleration in dual harmonic buckets

shown in Fig. 8. The phase between both cavities is well adjusted over the full frequency range from 800kHz to 5.4MHz.

BENEFITS & FUTURE APPLICATION

The next step will be the integration of the CEL functionality into a new DDS firmware revision. So far it appears that no additional hardware modifications will be necessary to push/extend the frequency range of the involved LLRF components to their physical limits. The so-called forward phase calibration principle can be used to generate an exact phase reference directly at the place where it is needed. For example, phase deviations can be monitored via a DSO somewhere in the supply room or in the control centre. This method potentially could be used for phase linearization of pre-amplifier and solid-state power amplifier without using a control loop.

Multi parameter delay correction, depending on frequency, harmonic numbers (switched), variable signal path and temperature variation give more liberty in designing synchronizing topologies.

CONCLUSION

The problem of a nonlinear phase response of the DDS generated references at multi harmonics as fixed by individual configuration of real-time calibration electronics. The selection of phase characteristics can be done by simple modification of the electronic configuration.

ACKNOWLEDGMENT

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