GSI – Memo	**Nr.:** 26102010
Beam Experiment 4:2:1 Bunch Merging in SIS18	**Name:** H. Klingbeil, U. Laier, K.-P. Ningel, B. Zipfel

1. Introduction

The experiment described here took place on October 19th, 2010. In the document at hand, preliminary results are summarized. The detailed analysis still has to take place.

Objectives

The main objective of the experiment was to prepare the control system integration of the multi-harmonic LLRF system. For this purpose, a use-case scenario described in [3] was defined. The 4:2:1 bunch merging use case was chosen since it contains a significant amount of complexity that has to be considered for the control system integration. This complexity is inevitable for the realization of the SIS18 upgrade and FAIR.

It has to be emphasized that no optimization with respect to the physical settings was planned or performed. For example, a large time span was chosen for the whole process, and only linear amplitude ramps instead of iso-adiabatic ramps were used for the sake of simplicity. Furthermore, the beam current was comparatively small.

All these aspects, however, are not relevant for the control system integration. They will be considered as soon as the control system integration is completed.

Setup

For internal reference, the measurement setup is shown in the following diagram. It is important to mention that almost the same system topology was chosen as for the dual-harmonic scenario tested in a previous beam experiment [4]. In the final configuration, no modifications will be required for dual harmonic operation, bunch splitting/merging or any other multi-harmonic use-case. Even though this final configuration has not been achieved yet, the present beam experiment and the beam experiments described in [4,7,8] serve as a verification of the planned FAIR LLRF topology for synchrotrons and storage rings.

The preparations that were specifically necessary for the machine development experiment (MDE) are described in detail in [6].

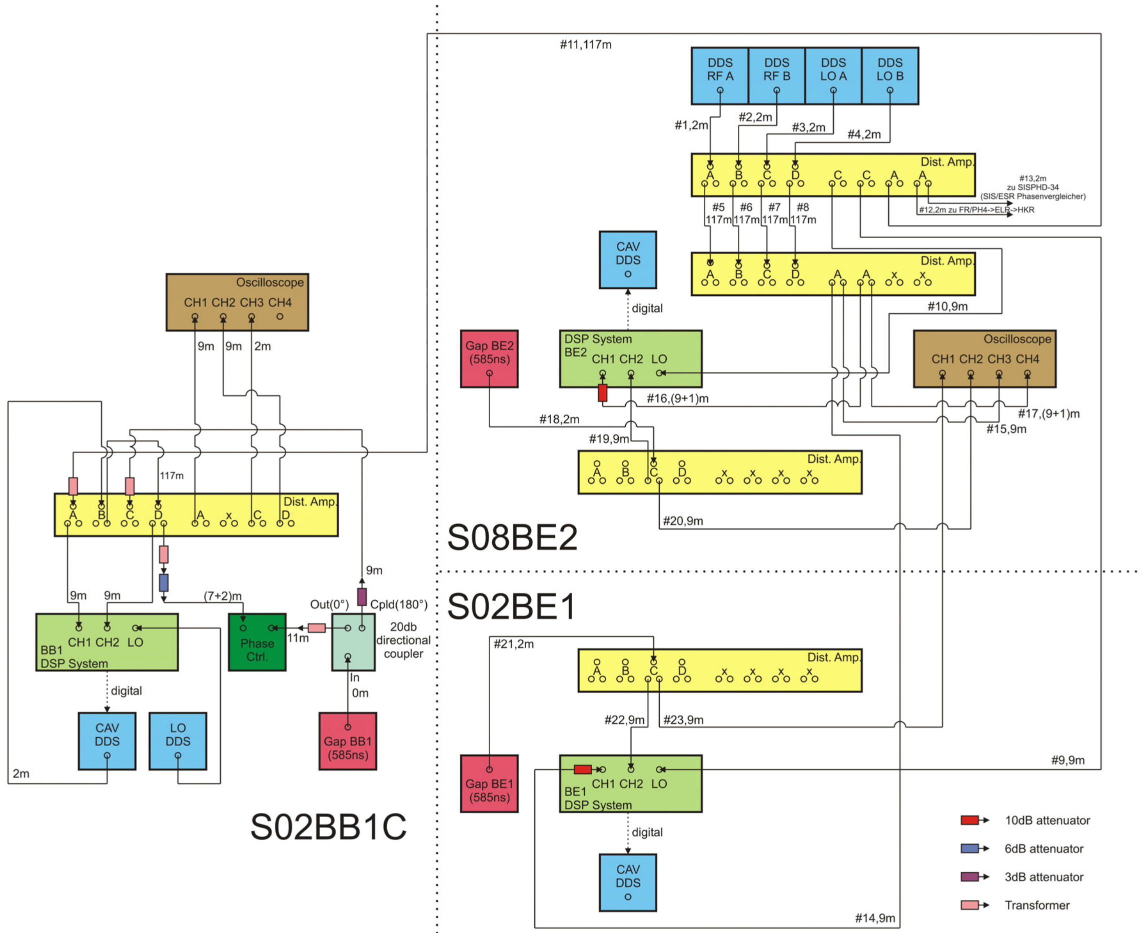

Figure 1: New Standard SIS18 LLRF System Topology [5]

2. Procedure

The main parameters for the experiment are listed in the following table:

Ion species	$^{238}U^{73+}$
Injection Energy	11.4 MeV/u
Extraction Energy	variable such that 3.2 MHz < $f_{RF,BE1}$<4.5 MHz

The cavity S02BE1 was temporarily operating at h=4 and temporarily at h=1, the cavity S08BE2 was permanently operating at h=2.

Since for the sake of simplicity the central control system was used to generate standard ramps for acceleration, a debunching of the beam on flattop was performed. This allowed the ring RF group to manually generate ramps in order to perform the bunch merging process. In future standard operation, such a de- and rebunching process on flattop will of course not be used since all ramps will then be created by the central control system. The simplification in the experiment has no implications on the technical verification.

The existing control system (including the latest modifications) delivered the following ramps:

- S00BE_FS: Revolution frequency (h=1, new device)
- S02BE1FS: Ramp for cavity frequency (h=4 during acceleration and a step from h=4 to h=1 during the flattop bunch merging process)
- S02BE1A: Standard ramp for cavity amplitude (acceleration at h=4 and debunching on flattop)
- S08BE2FS: Ramp for cavity frequency (h=2, but limited to the range 800 kHz...5.5 MHz)
- S08BE2A: Ramp for cavity amplitude (zero since the ramps were generated by the RF department)

In the RF supply room BG1.016, the following ramps were generated manually:

- Additional amplitude ramps for both cavities after flattop is reached
- Phase ramp for S02BE1 (In the note at hand, the cavity phase is defined as the difference between the phase of the gap signal and that of the group DDS. The group DDS signals were synchronized in such a way that all DDS signals may be regarded as cosine functions independent of the harmonic number).

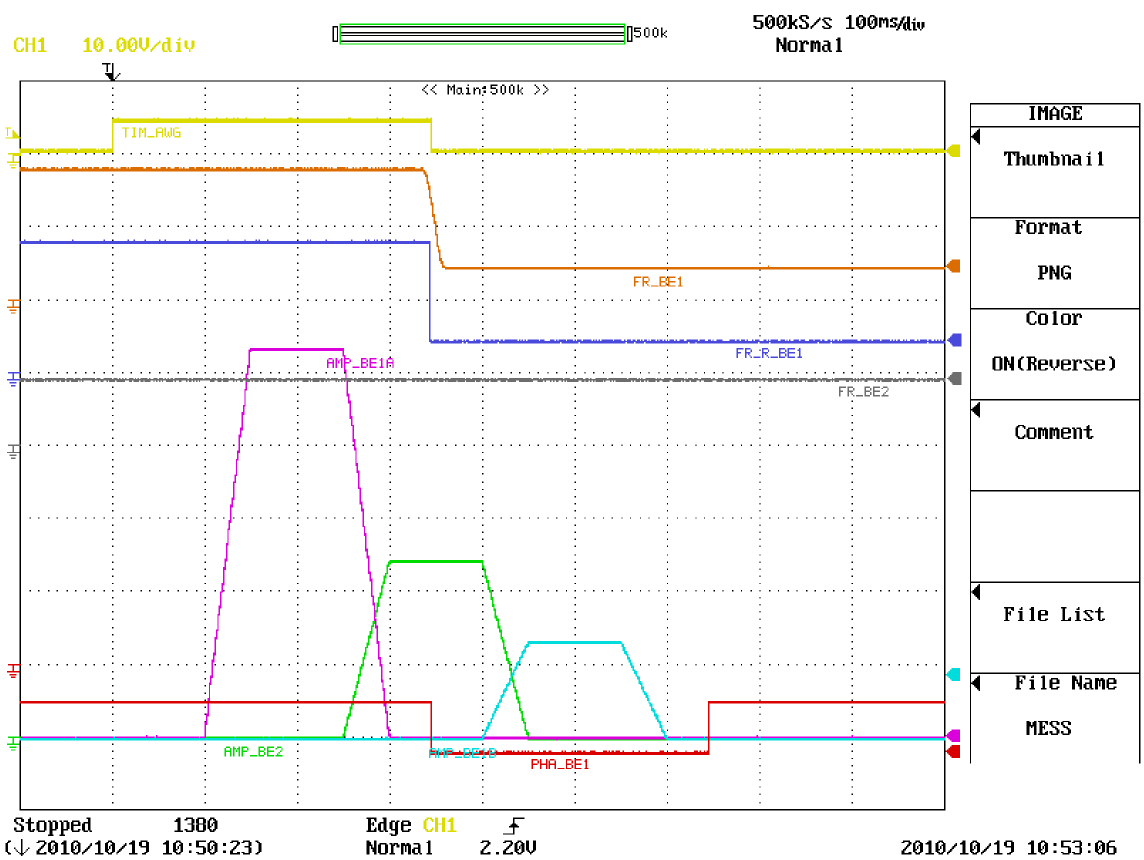

Figure 2: Oscilloscope plot of the generated ramps

Figure 2 shows the generated target value ramps:

- The sum of the pink and the turquoise curves served as an additional gap voltage for S02BE1.
- The green curve served as gap voltage for S08BE2.
- The red curve is the phase ramp for S02BE1. A different phase is required for operation at h=4 and at h=1, respectively, which leads to the step function.
- The orange curve is the frequency of the S02BE1 delivered by the central control system.
- The blue signal is the frequency of the switched group DDS signal for the S02BE1.

The height (amplitude) of two subsequent overlapping trapezoidal ramps differs by a factor of ½. This ratio was chosen in order to keep the overall bucket area (proportional to $\sqrt{U_{RF}/h}$) constant.

In order to simplify the setup, the phase of the S08BE2 was defined to be 0° (at h=2). This leads to a phase of the S02BE1 cavity of -90° for h=4 and +45° for h=1.

In principle, different choices for the phases are possible. It still has to be decided if this special choice of the phases is suitable for standard operation.

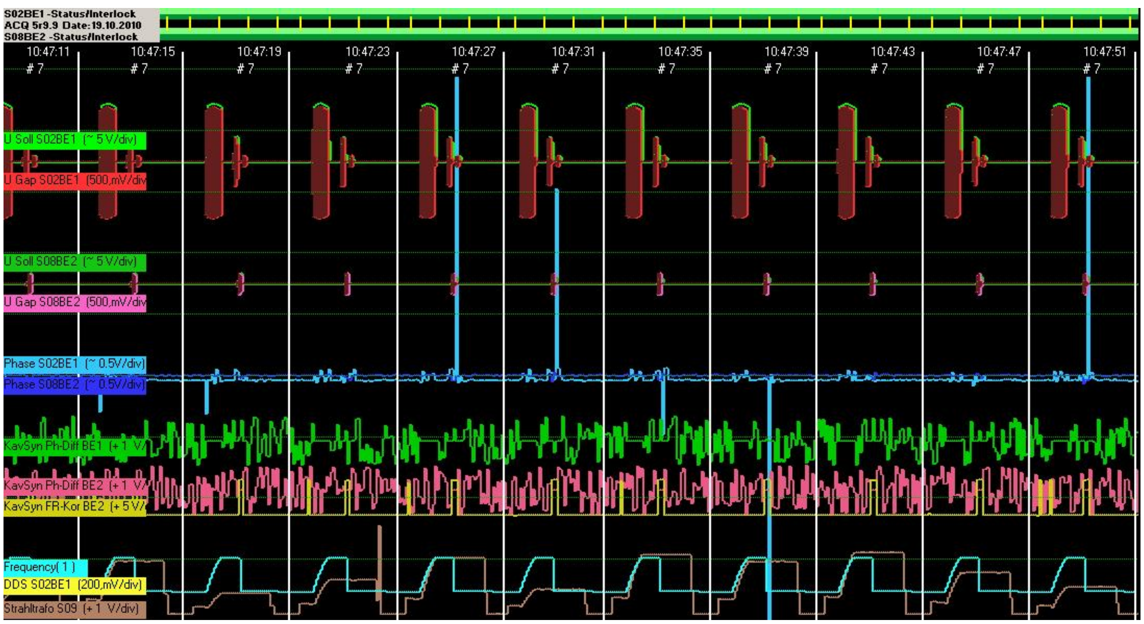

Figure 3: Ramps

Figure 3 shows an example for the generated actual ramps. The red curve shows the gap voltage of S08BE1 consisting of three phases:

- Capturing, acceleration, and debunching
- Bunching at h=4 and transition to h=2
- Transition to h=1

The pink curve shows the gap voltage of S02BE1.

The blue curve at the bottom shows the frequency of the S02BE1.

The grey curve at the bottom shows the beam current. It is obvious that no visible beam loss occurs during the 4:2:1 bunch merging process.

The other curves are not of interest in the scope of this note.

3. Measurement Results

Figure 4 shows a typical result that was obtained during the beam experiment. It is obvious that the bunches were merged in two steps as desired.

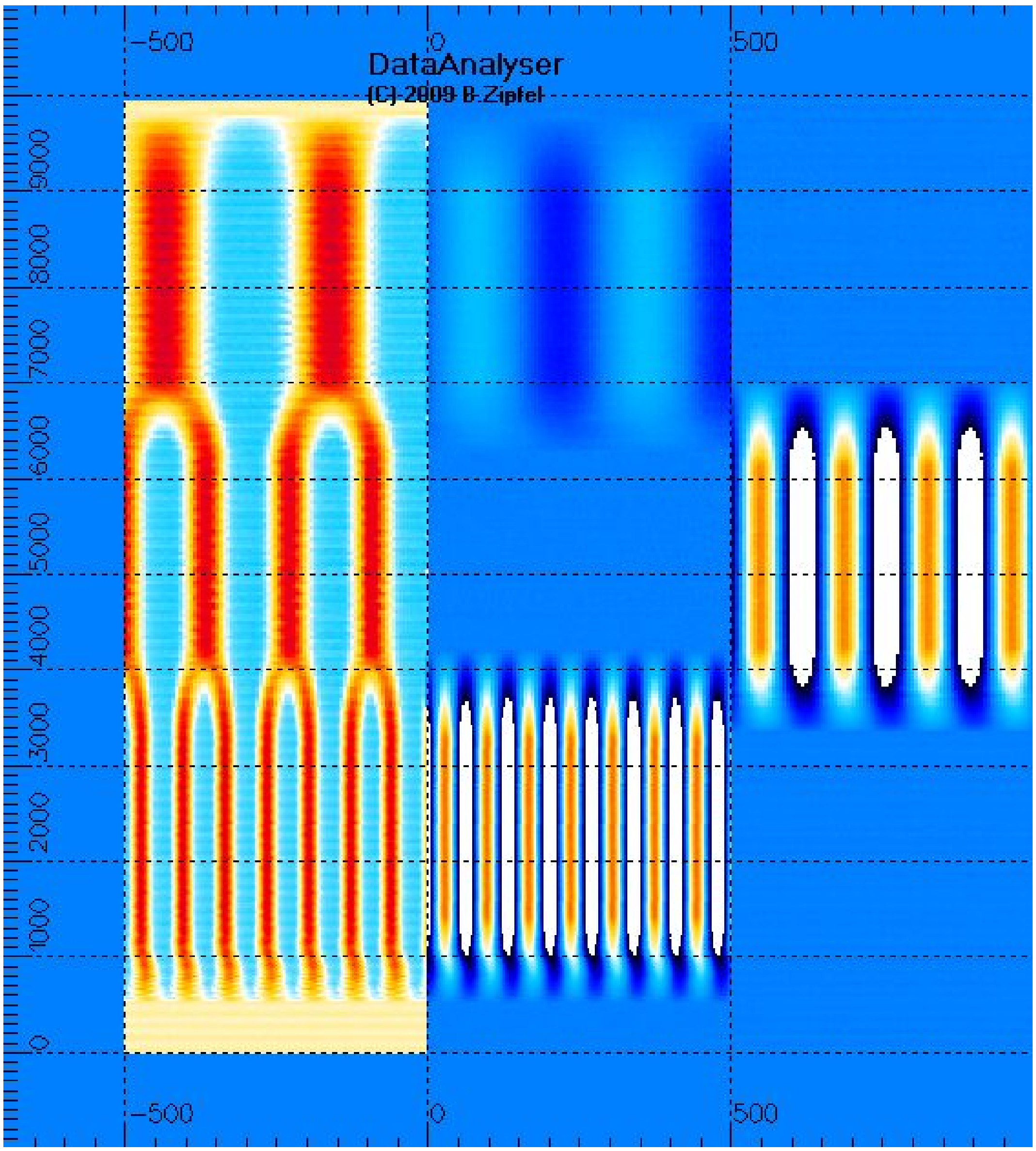

Figure 4: Waterfall plot (leftmost section: Beam signal (beam phase monitor S05DP3P), section in the middle: Gap voltage S02BE1, right section: Gap voltage S08BE2)

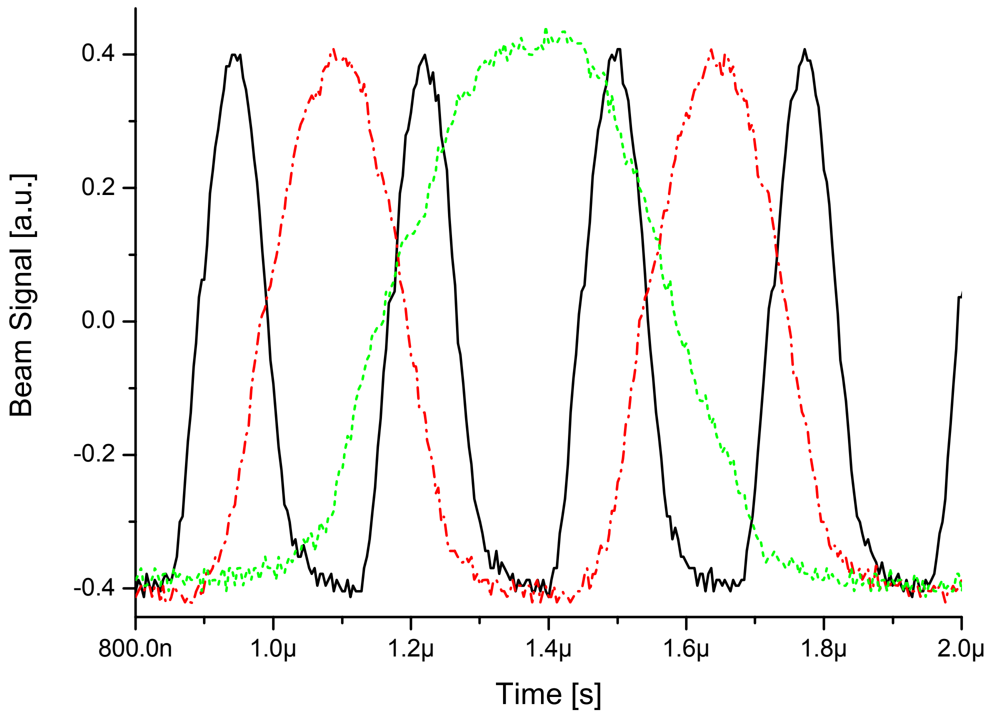

Figure 5: Bunch profiles before first merging (black solid curve), after 4:2 bunch merging (red dash-dotted curve) and after 2:1 bunch merging (green dotted curve)

Figure 5 shows the bunch profiles

- after adiabatic capturing on flattop (black solid curve),
- after the first bunch merging process (red dash-dotted curve), and
- after the second bunch merging process (green dotted curve).

In this case (for internal use: measurement 061), the phases were set in an optimal way such that no visible bunch disturbances are present.

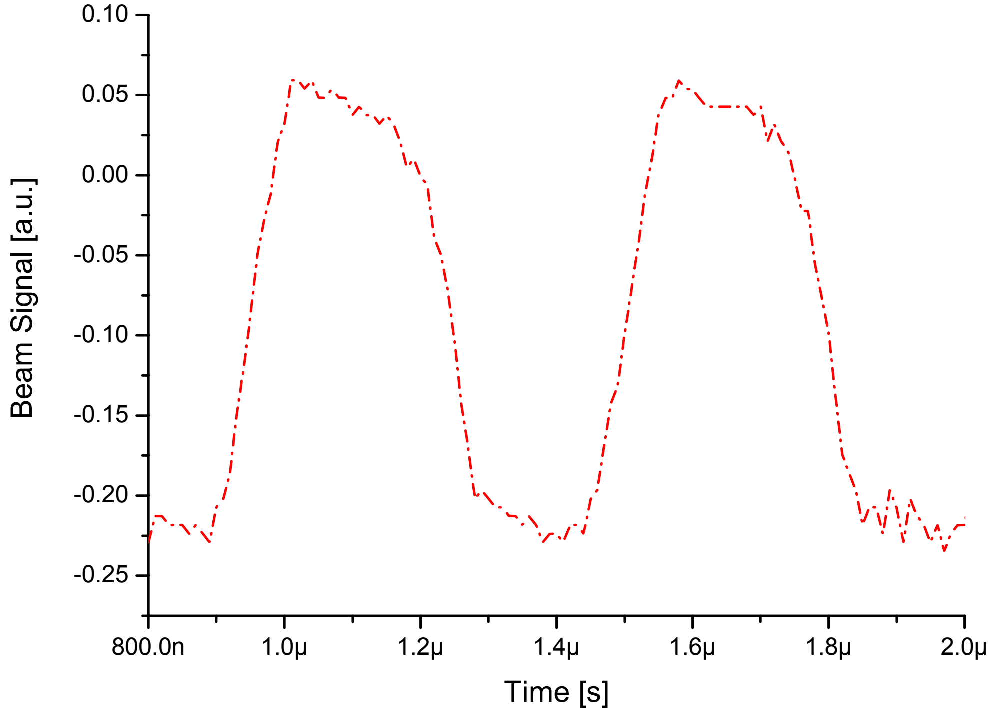

Figure 6: Bunch profiles after 4:2 bunch merging, 10° phase error

Figure 6 shows the bunch profiles if the phase intentionally deviates by 10° from the optimum value (for internal use: measurement 025). A slope of the merged bunch is clearly visible.

First analyses have shown that phase deviations of ±2° from the optimum value do not lead to visible deformations of the merged bunches. This confirms the results from the dual harmonic experiments [4,7,8] that an accuracy of better than ±3° should be reached under dynamic conditions.

4. Calibration

The experiment showed that the cavity phase may in principle be chosen based on theory formulas. However, a frequency-dependent phase correction was required in order to obtain symmetrical bunches after the merging process.

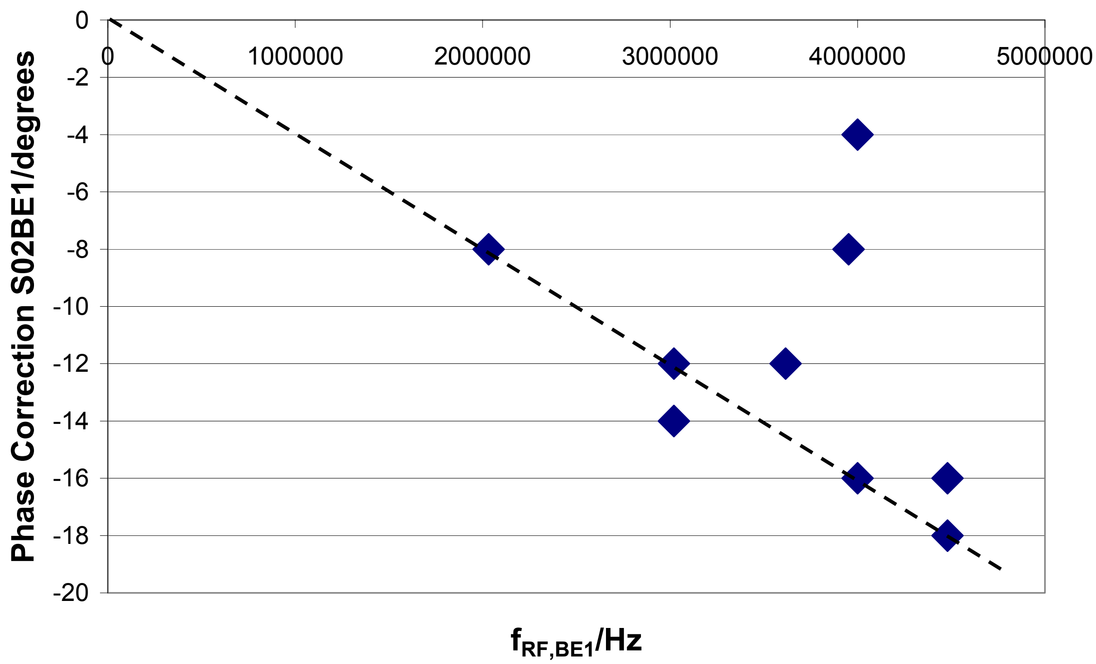

Figure 7: Calibration of Phase S02BE1

The markers in Figure 7 show calibration settings for which a symmetrical bunch shape was obtained. For some frequencies the result is very sensible to the calibration settings whereas for other frequencies the result does not depend significantly on small calibration changes.

An important result, however, is the observation that the linear calibration curve (dashed line in the diagram) may be used to obtain good results for the bunches (the markers above the linear curve also lead to good results, but this does not contradict the statement). Such a linear curve was expected as the most simple calibration scheme since it corresponds to constant delay errors of the LLRF system (in agreement with [4]). There is still some uncertainty that a linear calibration scheme will be sufficient for all operating conditions. But it is clear that such a calibration will be sufficient for control system integration with theoretical set values. In case the results should not be optimal under certain operating conditions, more detailed machine development experiments will be possible since the setup will be simpler.

5. Next Steps

5.1. Central Control System

- Two new phase ramps S02BE1P and S08BE2P have to be generated by the central control system (new devices).
- A standard ramp generation algorithm has to be defined which will allow 4:2:1 bunch merging during normal operation (proposal RF department).
- It has to be discussed which RF signals will be used in future for the timing generator (kicker control).

Even if the 4:2:1 bunch merging process should not be required for standard operation in SIS18, an implementation of this scenario or a similar one is important since such a control system integration will be needed for all further multi-harmonic operating modes such as the more complicated dual harmonic operation.

5.2. LLRF System

- A series solution for the phase calibration has to be implemented.
- A series solution for the phase reset of the group DDS units has to be implemented.

6. Conclusion and Outlook

The measurement results clearly show that the multi-harmonic LLRF system works properly. Therefore, the LLRF system topology (also for FAIR) was fully confirmed.

It was confirmed that the theoretical ramps allow a proper 4:2:1 bunch merging process. Therefore, it is possible to define a fixed algorithm for calculating the target ramps.

From today's point of view, all necessary calibrations can be performed inside the LLRF system.

The results show that the control system integration for this bunch-merging scenario can be finalized. After this is completed, it will be possible to optimize the data generation in order to minimize the process time and in order to improve the bunch shape. An algorithm for defining the phase and amplitude ramps will be proposed by the RF department.

7. Acknowledgements

The following persons (alphabetical order) have contributed significantly to the experiment:

- P. Kainberger
  - Preparation of control system hardware and software (SE)
- H. Klingbeil
  - LLRF design concept
  - Closed-loop control DSP system, firmware and host software (including phase ramp processing)
  - Trigger software
  - Participation in machine experiment
- U. Laier
  - Prototype & measurement setup
  - Measurement data analysis
  - LLRF design concept
  - Participation in machine experiment
- D. Mondry
  - Preparation of the measurement setup & infrastructure
- P. Moritz:
  - Acquisition PC (screenshots)
- K.-P. Ningel (for the beam experiment measurement setup)
  - Prototype & measurement setup
  - AWG control software
  - Trigger hardware
  - Data acquisition (e.g. LeCroy scope) and analysis
  - Participation in machine experiment
- S. Reimann
  - Ramp generation (especially the new revolution frequency ramp and the frequency jump)
- G. Riehl
  - Nodal software for controlling the operating modes
- S. Schäfer
  - Fiber-optical hub hardware & software (for the routing of phase and frequency ramps via optical fibers)
  - CCS-FIB hardware & software (for control system access)
- P. Schütt
  - Control system preparations
  - Machine settings
- P. Spiller
  - Approval of beam time for MDE
- C. Thielmann
  - DDS firmware development
  - Synchronization of DDS units (using external trigger pulses from TIF)
  - General support during preparation phase
  - Analog-to-digital ramp converter (for phase ramps)
  - Participation in machine experiment
- T. Winnefeld
  - Preparation of the measurement setup & infrastructure

- T. Wollmann
    - FIB for distribution amplifier (for access via central control system)
- B. Zipfel
    - Prototype & measurement setup
    - Generation of online waterfall plots
    - Measurement data analysis
    - Participation in machine experiment

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8. References

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