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Beam Experiment Stationary Dual Harmonic Operation under High- Intensity Conditions	Name: H. Klingbeil, U. Laier, K.-P. Ningel, B. Zipfel

1. Introduction

The experiment described here was initiated and supervised by P. Spiller. Data generation was supported by P. Schütt and S. Reimann. The experiment took place on November, 26th, 2010. In the document at hand, preliminary results are summarized. The detailed analysis still has to take place.

Participants

- P. Spiller
- H. Klingbeil
- U. Laier
- K.-P. Ningel
- C. Thielmann
- B. Zipfel

Objectives

The main objective was to generate a dual harmonic bucket under stationary conditions at injection energy using the DSP/FPGA-based cavity synchronization system [1, 2] and to compare it with a single-harmonic bucket at different beam intensities. Especially the beam loss during a long injection plateau was of interest.

The experiment may be regarded as a successor of previous machine experiments that served as a verification of the technical system setup for dual harmonic operation [3, 4].

Procedure

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

Table 1: Experiment Parameters

Ion species	$^{238}\text{U}^{73+}$
Injection Energy	11.4 MeV/u
Amplitude S02BE1 on injection plateau	12 kV, h=4
Amplitude S08BE2 on injection plateau	6 kV, h=8
DC beam current	0.15 mA and 3 mA, respectively

The central control system provided the revolution frequency ramp and the frequency ramps for both cavities. Furthermore it provided the amplitude for the cavity S02BE1 for acceleration and a long injection plateau with zero voltage. The control system amplitude for the S08BE2 was set to zero.

The amplitudes for both cavities during the injection plateau were generated manually using arbitrary waveform generators (AWGs).

The development of the beam current was observed while the stationary bucket was present. One virtual accelerator was used for a single harmonic ($h=4$) bucket, a different virtual accelerator was used for the dual harmonic bucket (with the same voltage for the first harmonic).

2. Setup

At the beginning of the experiment, several setup changes were necessary to allow high beam intensities and to obtain a good bunch shape (for non-optimal setups, triangular bunches were temporarily observed). These optimizations were not documented. At the end of the setup procedure, the following settings were fixed:

- The working point 4.17/3.29 was chosen
- A voltage of 12 kV at $h=4$ and of 6kV at $h=8$ was chosen
- An iso-adiabatic ramp was chosen for both harmonics (start value of 200V for BE1, 100V for BE2, rise time 100 ms)
- The ratio between the amplitudes of both cavities/harmonics was always $\frac{1}{2}$ and the ramps were chosen synchronously such that a dual harmonic bucket was generated from the very beginning (direct adiabatic capture of coasting beam into a dual-harmonic bucket).

All results summarized in this note refer to these settings if nothing else is explicitly stated.

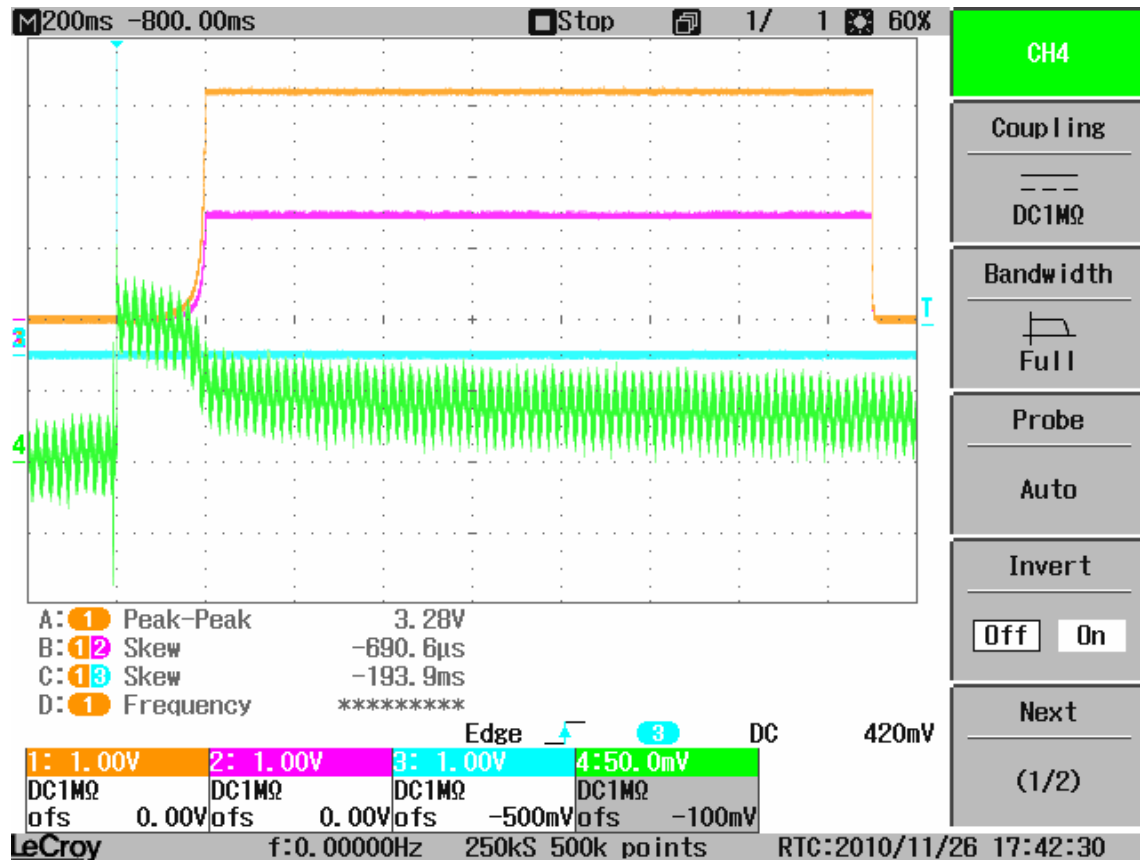


Figure 1: Ramps and beam current, measurement 026, $I_{B,DC}=0.15$ mA, $6 \cdot 10^7$ particles

Figure 1 shows an example for the generated ramps. The orange curve shows the $h=4$ amplitude, the pink curve the $h=8$ amplitude. The 100ms ramp-up time starts about 100ms after beam injection. The green curve shows the signal of the beam current transformer.

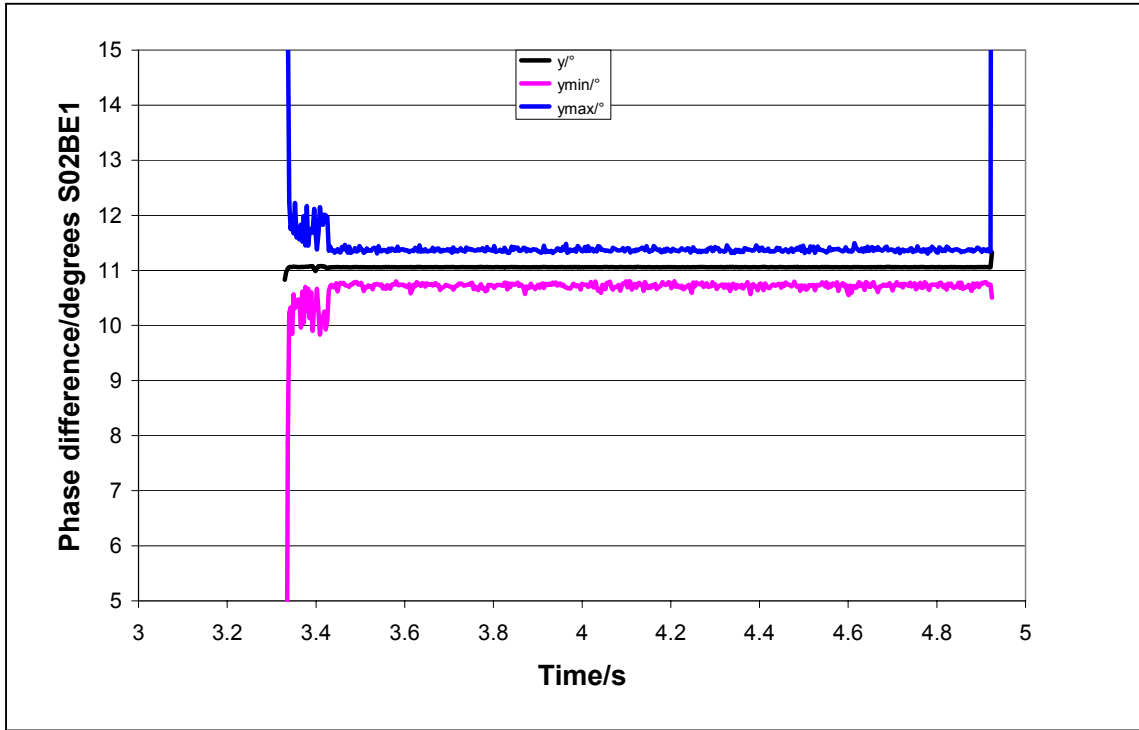


Figure 2: Phase of gap voltage BE1 (h=4) with respect to reference DDS (measurement 026)

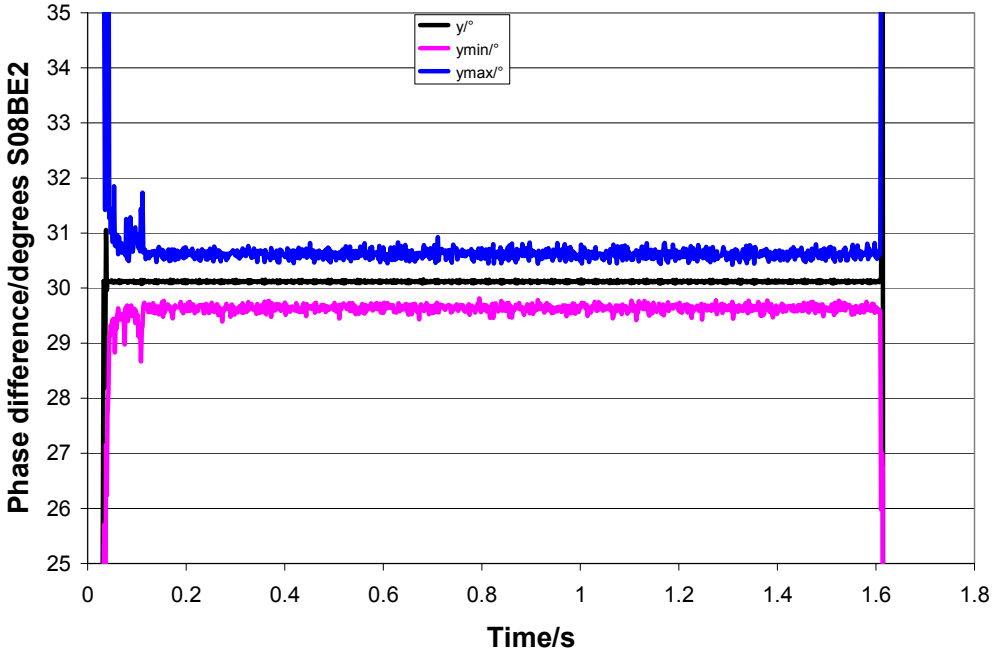


Figure 3: Phase of gap voltage BE2 (h=8) with respect to reference DDS (measurement 026)

Figure 2 and Figure 3 shows that the control loops for cavity synchronization work properly. A maximum deviation of about $\pm 0.5^\circ$ was reached in steady state. Even during ramp-up, under AGC (Automatic Gain Control which ensures that the ADCs

are operating in a suitable range) operation, a deviation of better than $\pm 2^\circ$ is reached as specified.

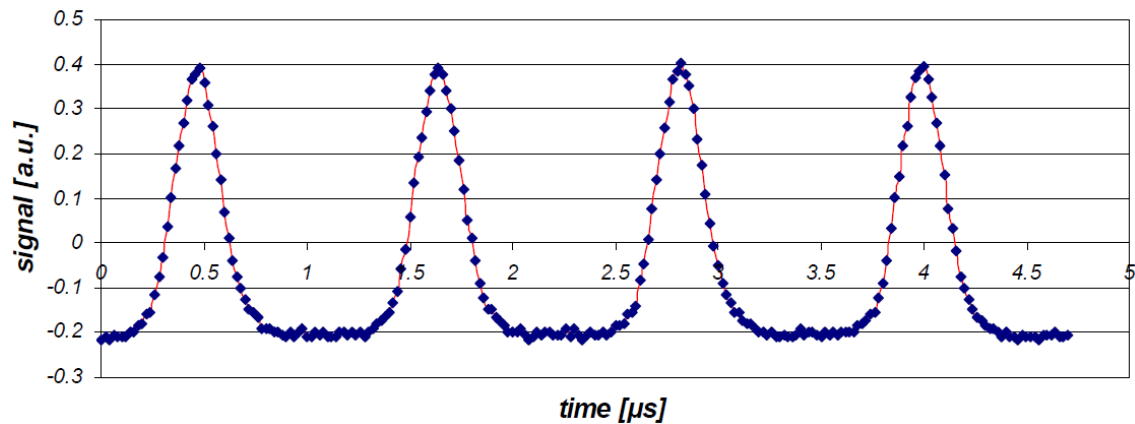


Figure 4: Bunch Profile Single-Harmonic Operation (B. Zipfel)

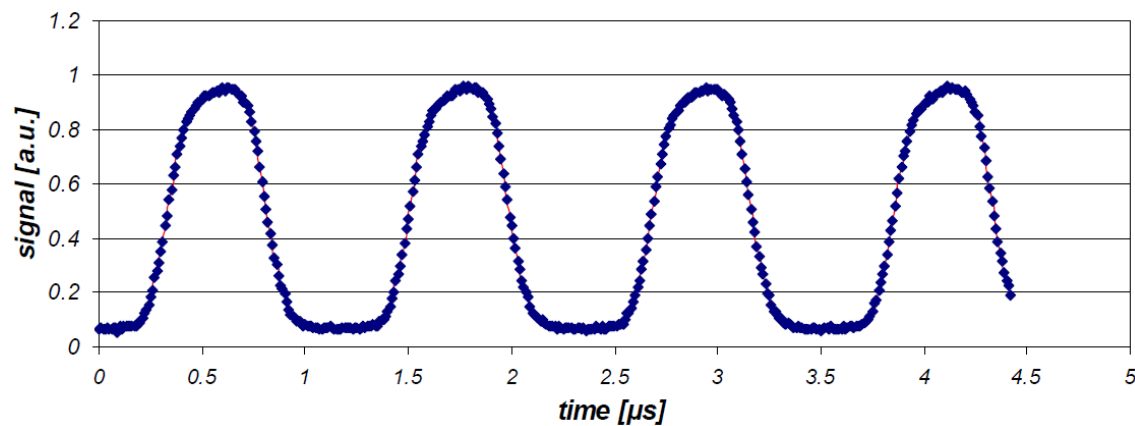


Figure 5: Bunch Profile Dual-Harmonic Operation (B. Zipfel)

During the setup, it was checked whether the bucket generation by the digital LLRF system was performed properly. As Figure 4 and Figure 5 indicates, the bunch shape shows the expected behavior (flattening of bunches due to the dual-harmonic operation, increased bunching factor).

3. Beam Current at RF Capture

The main purpose of the experiment was to analyze the behavior of the beam current during the stationary bucket period and to compare the single-harmonic case with the dual-harmonic one. It turned out that an anomalous behavior of the beam current is observed already during the capturing process. This is discussed in this chapter.

3.1. Beam Current Loss

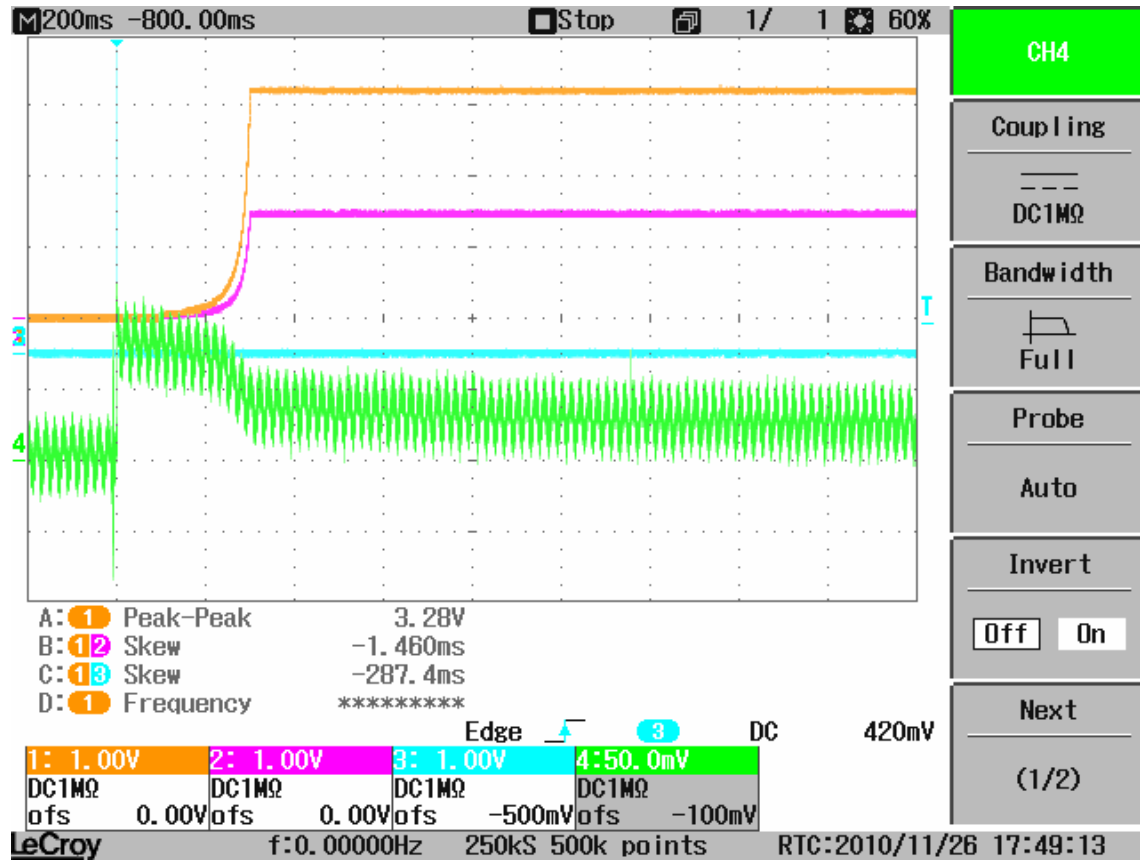


Figure 6: Ramps and beam current, measurement 029, $I_{B,DC}=0.15$ mA, $6 \cdot 10^7$ particles – Capture ramp time increased to 200 ms.

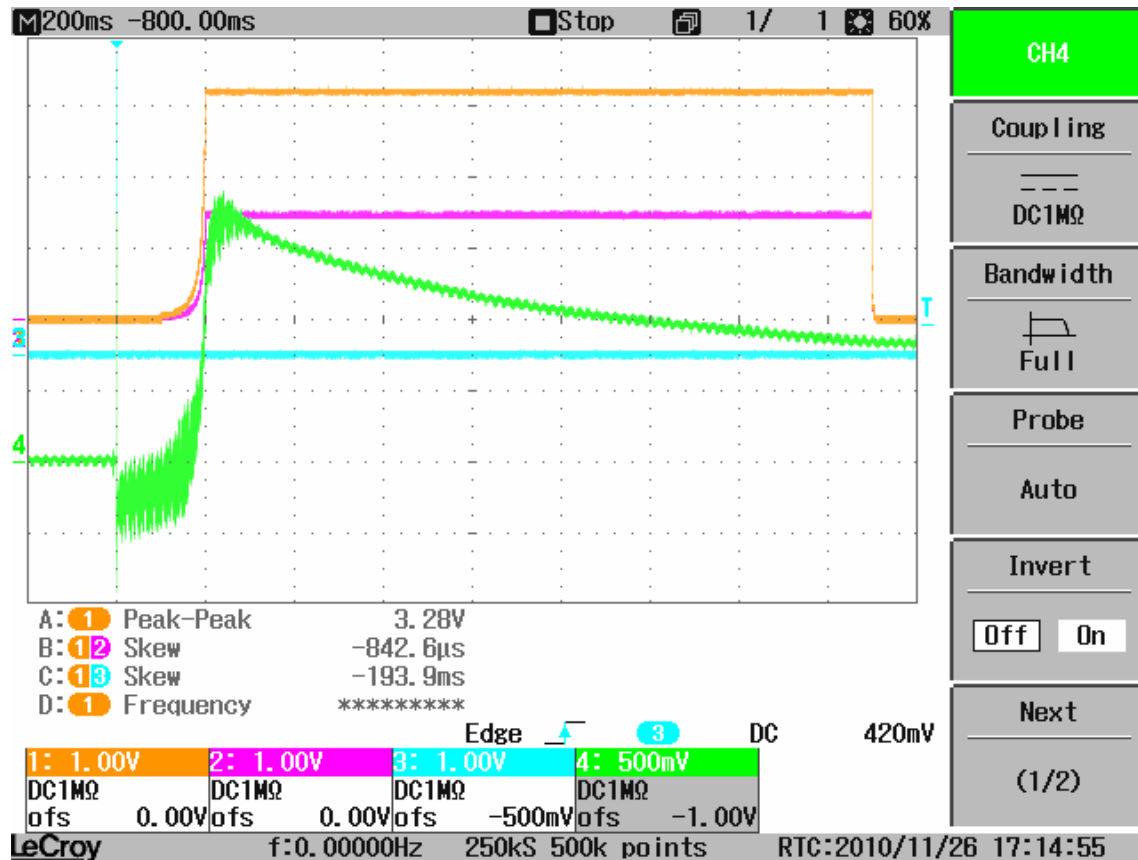


Figure 7: Ramps and beam current, measurement 008, $I_{B,DC}=3$ mA, $1,2 \cdot 10^9$ particles

The beam current transformer signal in Figure 1 shows a large decrease of the beam current when the RF capturing process starts. Such a decrease has often been observed in the past, both during normal operation and during machine development experiments. We will now discuss only this decrease – the exponential decay that is observed during constant gap voltage amplitude is discussed in the next chapter.

For the rapid decay at RF capture, the following observations were made:

- For low beam currents, the current decreases by about 50%. A comparison of Figure 1 and Figure 6 shows that this decrease does not depend on the ramp time.
- As Figure 1 shows, no significant change of the beam current is observed at the end of the voltage plateau. Therefore, the output of the beam current transformer seems to be reliable since coasting beam and bunched beam results are equivalent.
- As Figure 8 and Figure 9 shows, the phase of the beam signal does not show any drift in comparison with the reference DDS. This indicates that the RF frequency was properly adapted to the revolution frequency of the particles.

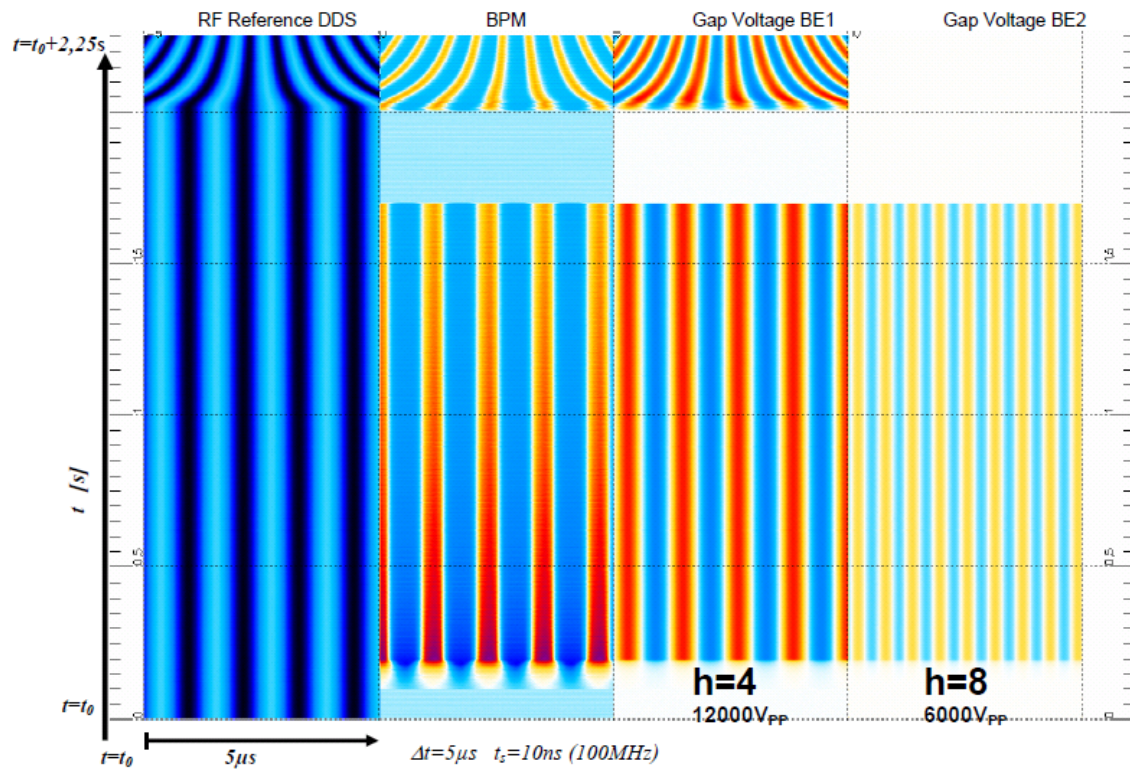


Figure 8: Waterfall plots (by B. Zipfel) for measurement 008, $I_{B,DC}=3$ mA, $1.2 \cdot 10^9$ particles

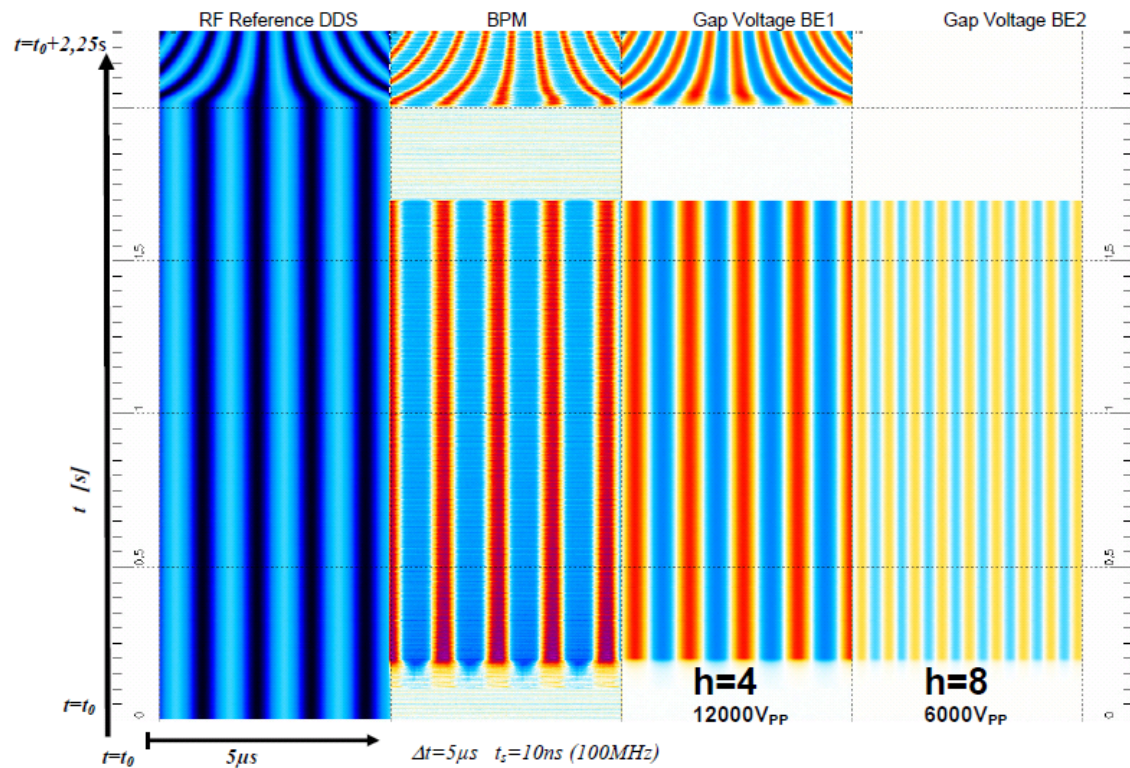


Figure 9: Waterfall plots (by B. Zipfel) for measurement 026, $I_{B,DC}=0.15$ mA, $6 \cdot 10^7$ particles

Interpretation

- A beam loss can only be explained by particles deviating significantly from their expected transverse position.
- A worst-case frequency mismatch of $1 \cdot 10^{-3}$ would result in an additional momentum spread of about $5 \cdot 10^{-4}$ which is the same order of magnitude as the momentum spread of the original beam. Since such a large frequency mismatch can definitely be excluded, it is unlikely that it causes the effect.
- Further effects like RF noise, ripple etc. are assumed to be much smaller and are therefore also unlikely as a cause for the problem.
- Since the effect is present at small beam currents, intensity-dependent instabilities are also unlikely as a cause.
- For the chosen gap voltage of 12kV, we calculated a single-harmonic bucket height of $\Delta p/p = \pm 5.2 \cdot 10^{-3}$. This value leads to the question whether the energy acceptance of the machine was the limiting factor (e.g. by collimator positions). This could explain why the problem does not depend on the intensity. Simulations performed by B. Zipfel which assumed a momentum spread that is too large for the machine acceptance showed a similar decrease of the beam current as it was observed in the experiment.

Conclusion: The cause of the problem has to be investigated in future machine experiments. The problem itself, however, has no effect on the observations in the following chapters since they deal with the long-term behavior of the beam at constant RF voltage after the "anomalous loss period" is over.

3.2. Beam Current Signal Increase

In addition to the beam loss effect discussed before, a different strange effect is visible in Figure 7. The beam current seems to increase after injection which should be impossible. It is not clear whether this problem is related to the settings for the beam current transformer. The problem is only observed at comparatively high beam currents (3 mA, Figure 7, Figure 12, Figure 13). At low intensities the behavior is as expected (see Figure 1, Figure 6).

4. Measurement Results

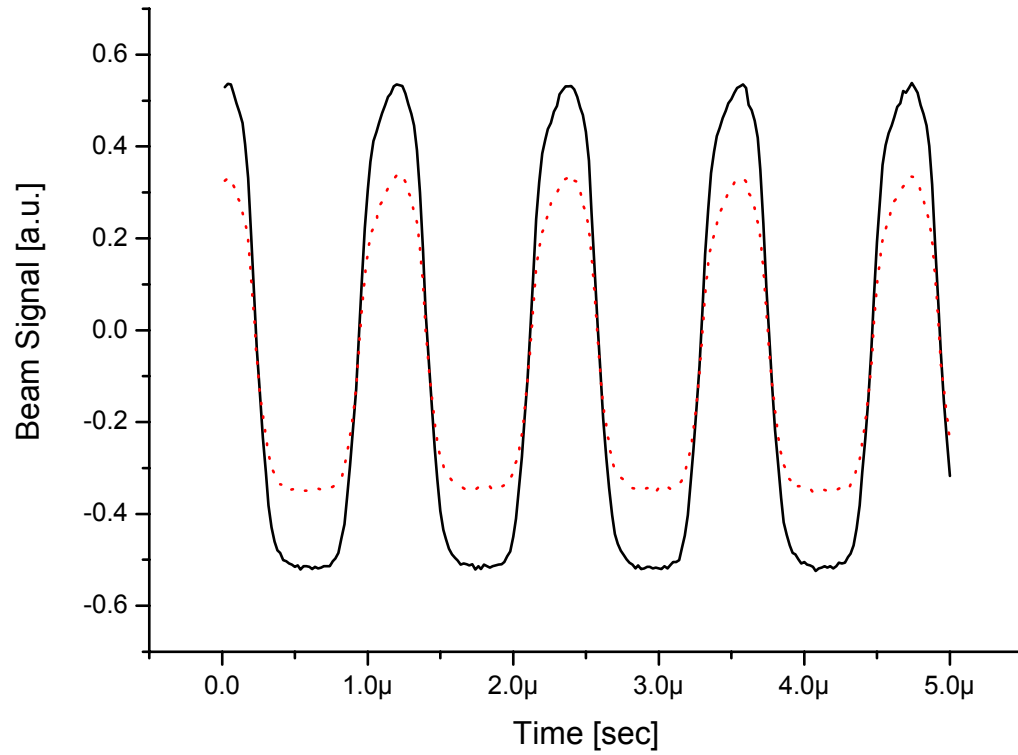


Figure 10: Bunch Profile, Measurement 008, $I_{B,DC}=3$ mA, $1,2 \cdot 10^9$ particles
(solid line: after 400ms, dotted line: after 1500ms) – decrease from 100% peak-peak to 60%
(K.-P. Ningel)

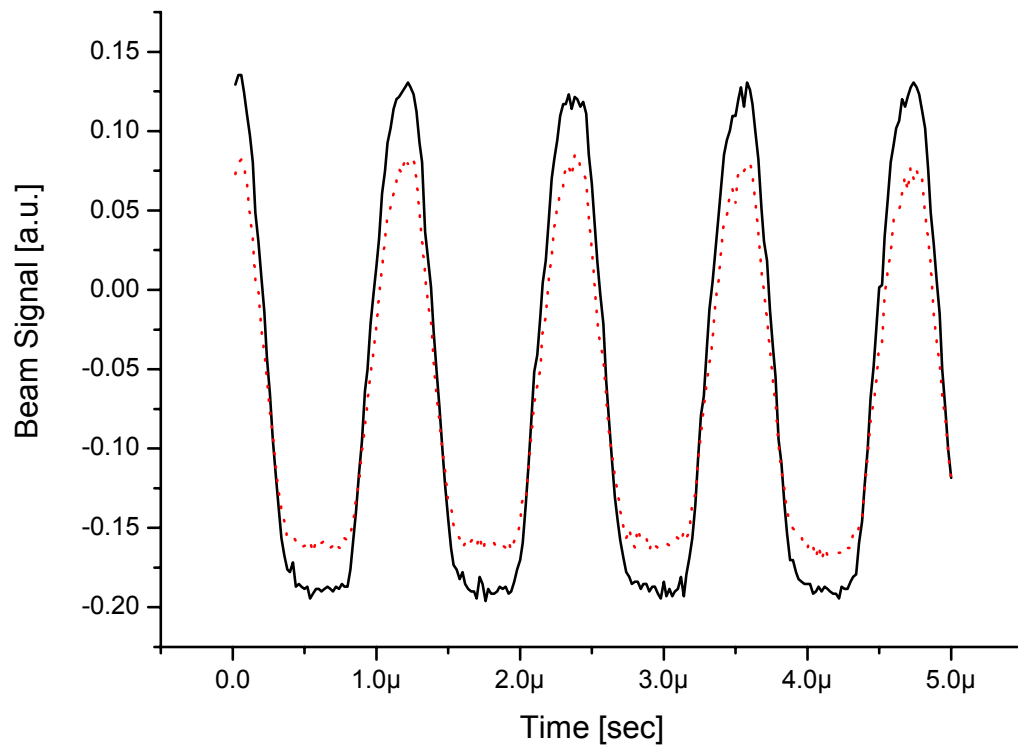


Figure 11: Bunch Profile, Measurement 026, $I_{B,DC}=0.15$ mA, $6 \cdot 10^7$ particles
 (solid line: after 400ms, dotted line: after 1500ms) – decrease from 100% peak-peak to 75%
 (K.-P. Ningel)

Figure 10 shows that the beam current decreases by about 40% in 1.1 s for a comparatively high beam current of 3 mA. If the beam current is reduced to 0.15 mA, this decrease is smaller (25%, see Figure 11).

Therefore, higher intensities lead to higher beam losses as expected.

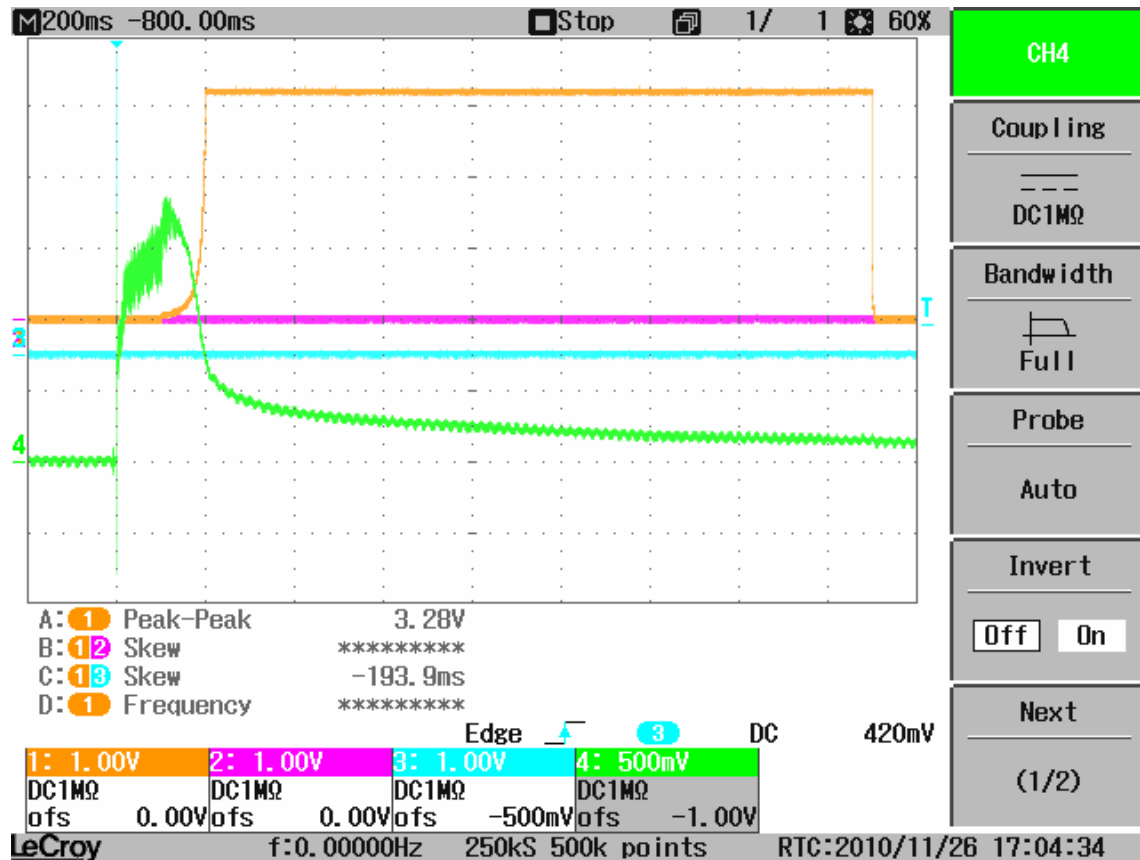


Figure 12: screenshot 007 (corresponds to measurement 008), single-harmonic bucket

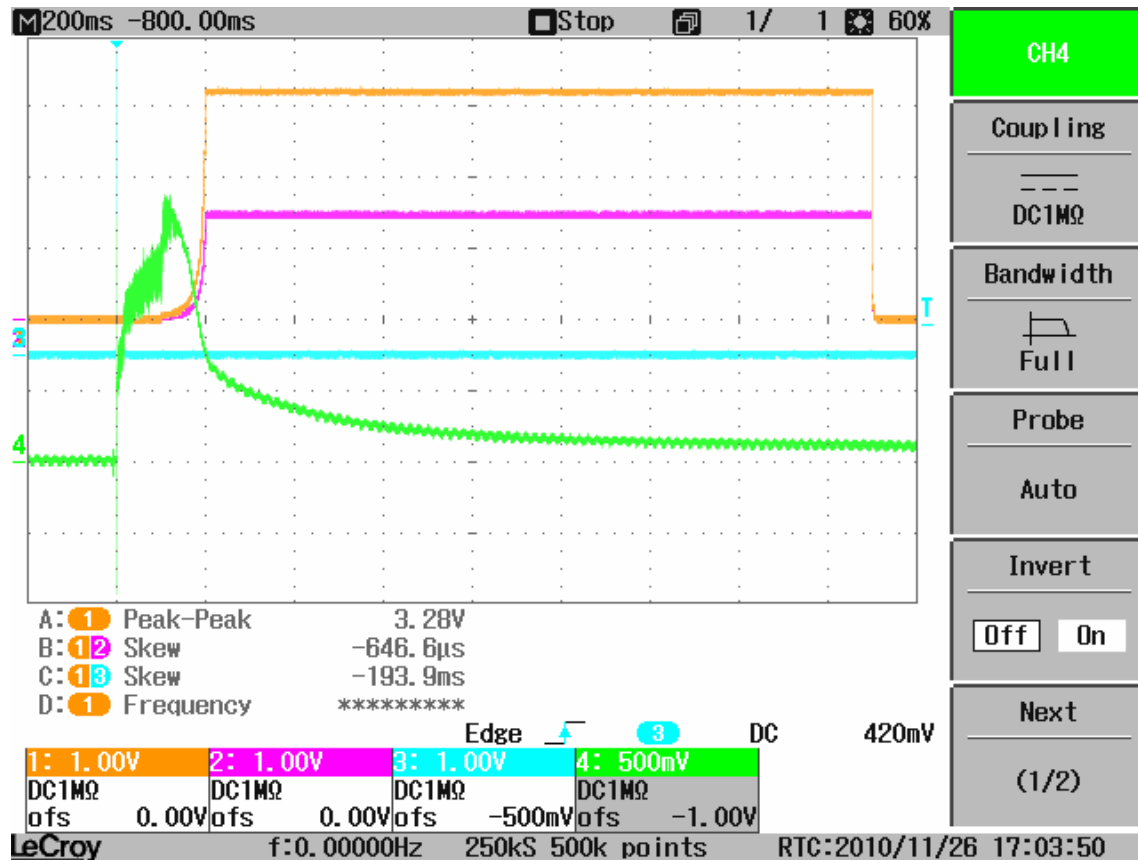


Figure 13: screenshot 006 (corresponds to measurement 008), dual-harmonic bucket

In Figure 12 (single-harmonic operation) and Figure 13 (dual-harmonic operation) the beam current decrease is shown for a comparatively high beam current of 3 mA. A slight difference with respect to the beam current decrease is observed between the dual-harmonic and the single-harmonic bucket if the diagrams are directly compared with each other. The dual-harmonic bucket shows a small improvement of the beam losses in comparison with the single-harmonic bucket.

It is not clear yet why only a slight improvement has been observed. Perhaps, the beam intensity limitation was not reached. Since the loss mechanism (which leads to the decrease that is observed here) has not been analyzed in detail yet, it is not clear whether a different limiting factor (e.g. vacuum) is present. Therefore, further beam experiments are necessary.

5. Conclusion

- The measurement results clearly show that the dual harmonic LLRF system works properly.
- The interpretation of the observed beam current behavior during RF capture is difficult, but these problems do not influence the results obtained for constant RF amplitudes.
- At constant RF amplitude, the dual-harmonic bucket only leads to small improvements with respect to the beam current decrease in comparison with the single-harmonic bucket. However, since the loss mechanisms are not clear yet, this does not mean that the dual harmonic operation will not show improvements under optimized machine settings.
- Future experiments are mandatory to clarify the observed effects.

6. References

- [1] H. Klingbeil: A Fast DSP-Based Phase-Detector for Closed-Loop RF Control in Synchrotrons, IEEE Trans. Inst. Meas., Vol. 54, No. 3, 2005.
- [2] H. Klingbeil, M. Kumm, P. Moritz and B. Zipfel: A Cavity Synchronization System for Heavy Ion Synchrotrons Based on DSP, DDS and FPGA Technology, Proceedings of the Workshop LLRF05, CERN, 2005.
- [3] K.-P. Ningel, H. Klingbeil, M. Kumm, U. Laier: "Beam Experiment Dual Harmonic Operation", GSI internal note no. 26052008.
- [4] H. Klingbeil, U. Laier, B. Zipfel: "Beam Experiment Dual Harmonic Operation with Acceleration", GSI internal note no. 10032010.