PRECISE VERIFICATION OF PHASE AND AMPLITUDE CALIBRATION BY MEANS OF A DEBUNCHING EXPERIMENT IN SIS18*

U. Hartel†, TEMF, Technische Universität Darmstadt, Germany
H. Klingbeil, TEMF, Technische Universität Darmstadt, Germany; GSI, Darmstadt, Germany
U. Laier, K.-P. Ningel, S. Schäfer, B. Zipfel, GSI, Darmstadt, Germany
J. Grieser, D. Lens, RTR, Technische Universität Darmstadt, Germany

Abstract

Several new rf cavity systems have to be realized for the FAIR[1] synchrotrons and for the upgrade of the existing GSI synchrotron SIS18 [1]. For this purpose, a completely new low-level rf (LLRF) system architecture [2] has been developed, which is now used in SIS18 operation. Closed-loop control systems stabilize the amplitude and the phase of the rf gap voltages. Due to component imperfections the transmission and the detection of the actual values lead to systematic errors without countermeasures. These errors prohibit the operation of the rf systems over the whole amplitude and frequency range within the required accuracy. To compensate the inevitable errors, the target values provided by the central control system are modified by so-called calibration electronics (CEL, [3]) modules. The calibration curves can be measured without the beam, but the desired beam behaviour has to be verified by experiments. For this purpose, a debunching scenario was selected as a SIS18 beam experiment that proved to be very sensitive to inaccuracies. In this contribution the results of this experiment are presented, showing for the first time at GSI by beam observation that the accuracy requirements are met based on predefined calibration curves.

INTRODUCTION

The actual amplitude and phase values of the rf gap voltages differ from the target values provided by the central control system (CCS), since component imperfections lead to a non-ideal frequency response over the whole amplitude and frequency range. The amplitude deviations of the two SIS18 cavities S02BE1 (abbr. BE1) and S08BE2 (abbr. BE2) are in between -10% and $+30\%$ without countermeasures. Furthermore, the phase deviations are -10° to $+10^\circ$ if no additional calibration is performed. Theoretical investigations and previous machine experiments demand an accuracy of $\pm 6\,\%$ for the amplitude and $\pm 3\,^\circ$ for the phase. Therefore, programmable CEL modules are used which modify the CCS target values depending on the frequency and/or[2] the target value itself. In advance, calibration curves are measured without the beam and programmed offline into the module. In order to verify the desired effect on the beam, a debunching scenario was developed and performed in a SIS18 beam experiment [4], which is presented in the following section.

Debunching Experiment

Starting the machine cycle with an injection energy of $11.2\,\mathrm{MeV/u}$, a $^{238}\mathrm{U}^{73+}$ beam of about $1 \cdot 10^9$ particles is accelerated up to a kinetic energy of $120\,\mathrm{MeV/u}$ or $600\,\mathrm{MeV/u}$, respectively and afterwards debunched at flattop energy. The standard ramps for the cavities are provided by the CCS, whereby only BE1 receives a non-zero voltage amplitude. In addition, a constant control voltage for the amplitudes of both cavities is added by manual setups over the whole machine cycle. A control voltage of $2\,\mathrm{V}$ ideally leads to an rf amplitude of $3.7\,\mathrm{kV}$ per cavity. Because the cavities are synchronized with opposite phase at the harmonic number $h = 4$ no residual voltage should be present at injection energy and after the debunching at flattop energy. The opposite phase[3] is realized by additional control voltages (see FIG. 1, BE1: $4.5\,\mathrm{V} \widehat{=} +90\,^\circ$, BE2: $-4.5\,\mathrm{V} \widehat{=} -90\,^\circ$).
By means of this dedicated experiment, the debunching quality at injection energy or at extraction energy can be investigated and minimized in a two-step process. For this optimization, the control voltage of the BE1 target phase is adjusted first and the control voltage for the BE1 target amplitude is adapted afterwards. This procedure allows us to verify the precision of the phase and amplitude calibration.

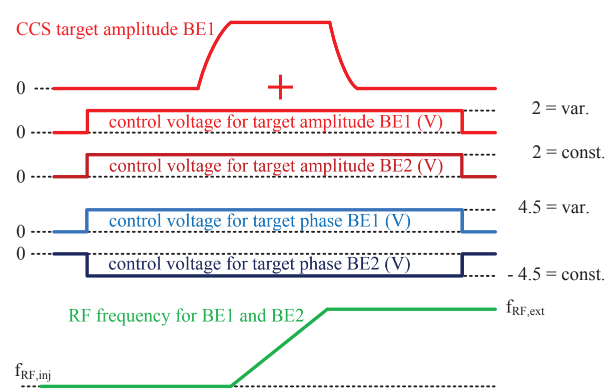

Figure 1: Schematic drawing of the cycle ramps.

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[1] **F**acility for **A**ntiproton and **I**on **R**esearch
[2] The phase correction is a function of the rf frequency, whereas the amplitude correction depends on both, the rf frequency and the target value itself.
[3] The phase is defined with respect to a common reference frequency.

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METHODS

Two-Step Optimization Process

As mentioned before, the control voltage of the BE1 target phase and of the target amplitude is adjusted to obtain a minimal bunching. Assuming an rf amplitude of BE1 which differs slightly by $\Delta\hat{u}$ from the rf amplitude of BE2 and a phase of BE1 which shows a small deviation ε from the desired $180\,^\circ$ with respect to the phase of BE2, the rf voltages with the phases φ_1, φ_2 or the rf angular frequency ω_{rf} are given by

$$u_{BE2} = \hat{u}_2 \cdot \cos\varphi_2 = \hat{u}_2 \cdot \cos(\omega_{rf}\, t)$$
$$u_{BE1} = \hat{u}_1 \cdot \cos\varphi_1 = (\hat{u}_2 + \Delta\hat{u}) \cdot \cos(\omega_{rf}\, t + \pi + \varepsilon)\ .$$

We obtain:

$$\begin{aligned} u_{tot} &= u_{BE1} + u_{BE2} \\ &= [\hat{u}_2 - (\hat{u}_2 + \Delta\hat{u})\cos\varepsilon]\cos(\omega_{rf}\, t) \\ &\quad + [(\hat{u}_2 + \Delta\hat{u})\sin\varepsilon]\sin(\omega_{rf}\, t) \end{aligned}$$

which leads to the total amplitude

$$\begin{aligned} \hat{u}_{tot} &= \sqrt{[\hat{u}_2 - (\hat{u}_2 + \Delta\hat{u})\cos\varepsilon]^2 + [(\hat{u}_2 + \Delta\hat{u})\sin\varepsilon]^2} \\ &= \sqrt{2\,\hat{u}_2\,(\hat{u}_2 + \Delta\hat{u})\,(1 - \cos\varepsilon) + \Delta\hat{u}^2}\ . \end{aligned}$$

According to

$$\frac{\partial\hat{u}_{tot}}{\partial\varepsilon} = \frac{\hat{u}_2\,(\hat{u}_2 + \Delta\hat{u})\sin\varepsilon}{\sqrt{2\,\hat{u}_2\,(\hat{u}_2 + \Delta\hat{u})\,(1 - \cos\varepsilon) + \Delta\hat{u}^2}} = 0$$

a minimum can be derived with respect to the phase deviation ε for $\sin\varepsilon = 0$. If the optimal phase has been found by adapting ε to zero, the second step is finding the best amplitude deviation ($\Delta\hat{u} = 0$) in order to avoid the bunching of the beam.

Measurement Evaluation

The measurement signals of the beam current and of the rf gap voltages are analyzed by means of a discrete Fourier transform. The debunching quality is checked by calculating the fundamental harmonic of the beam current measured with an FCT[4]. In addition to the amplitude of the fundamental harmonic, the baseline of the AC coupled FCT signal is determined. According to measurements of a slow DC transformer the number of particles in the accelerator is known and thus the DC current. The beam current amplitude of the fundamental harmonic can by evaluated in ampere by means of the baseline.
In addition, the rf gap voltages are provided by a gap voltage divider[5] per gap half for each cavity and measured with oscilloscopes. Hereby, the fundamental harmonic is calculated per signal and afterwards the Fourier coefficients of the four signals are summarized[6]. Depending on the added coefficients the amplitude per gap half, per cavity or an overall gap voltage is obtained. Furthermore, the phases between the halves for each cavity and the phase between the two cavities can be depicted.
Now, the overall gap voltage can be associated with the bunching level of the beam current. At this point it is obvious that the measured signal of the gap voltages, which is the basis for the calibration curves of the CELs, and the gap voltage, which is seen by the ions, is not necessary identical over the whole amplitude and frequency range due to imperfections of the transmission and of the detection. Therefore, only the proof of the desired beam behaviour verifies the amplitude and phase calibration realized by the CELs.

RESULTS

Phase Optimization

Figure 2a depicts the fundamental harmonic amplitude of the beam current as a function of the adjusted phase for the cavity BE1. The phase of the cavity BE1 is slightly shifted from the ideal value, while the phase of BE2 and the rf voltage amplitude per cavity is kept constant. A minimal bunching level is obtained if the control voltage of the target phase is between 4.375 V and 4.625 V. This voltage span corresponds to a phase deviation of $\pm 2.5\,^\circ$, which fulfils the required phase accuracy. For higher energies the optimal target phase can be identified even within a smaller range of less than $\pm 1\,^\circ$.
This result is confirmed by the overall gap voltage (cf. FIG. 2b). It was checked that the measured signals per gap half are in opposite phase[7], which shows the phase uniformity of the signal transmission from the cavity to the LLRF system. Furthermore, the rf amplitude deviation[8] between the gap halves is less than 2 %. This can not be taken for granted, since there are different steps of voltage division and the distance is more than 150 m. A minimum of the measured overall gap voltage obviously leads to minimal bunching level. In other words, the measured signals represent the actual phase of the gap voltage accurately, which ensures the desired beam behaviour.

Amplitude Optimization

Figure 3a depicts the fundamental harmonic amplitude of the beam current as a function of the adjusted amplitude for the cavity BE1. The identified optimal phase values of both cavities and the rf amplitude of BE2 are kept constant. A control voltage for the target amplitude between 1.95 V and 2.05 V, which corresponds to a deviation of ± 2.5 % from the theoretical value of 2 V, has to be adjusted to guarantee a minimal bunching level. At higher energies the range of the optimal value is even smaller.
Taking the overall gap voltage (cf. FIG. 3b) into account, the optimal value appears a little bit lower than the theoretical value, which is in compliance with the bunching level. Nevertheless, the requirements of the amplitude accuracy

[4] **F**ast **C**urrent **T**ransformer; Bergoz FCT-LD-260-50:1H [5]
[5] ratio 1/10000
[6] Adding the rf signals first and calculating the DFT afterwards leads to the same result.
[7] max. deviation $\leq 1\,^\circ$
[8] The deviation is even smaller at higher energies.

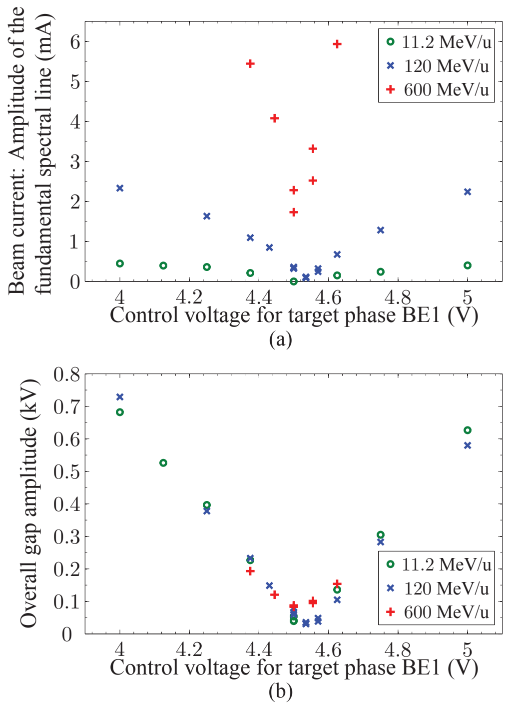

Figure 2: Phase optimization for the cavity BE1 (2 V control voltage for the target amplitude of both cavities, -4.5 V control voltage for the target phase of cavity BE2).

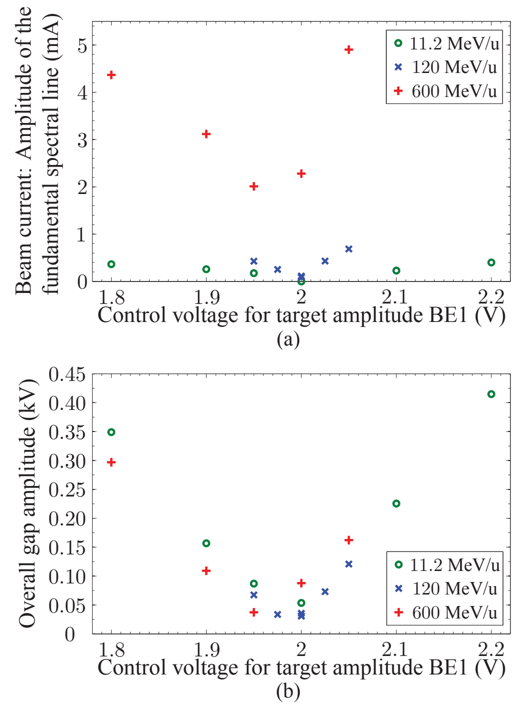

Figure 3: Amplitude optimization for the cavity BE1 (2 V control voltage for the target amplitude of the cavity BE2, optimal adjusted control voltage for the target phase of BE1 and -4.5 V control voltage for BE2).

are fulfilled. It has to be emphasized that the ratio between the control voltage and the measured gap voltage per cavity may differ[9] depending on the frequency and the target amplitude. Furthermore, the measured total gap voltage may differ from the voltage experienced by the beam. However, no significant deviation could be identified ($< 3\,\%$).
In addition, it has been proven that the phase stays constant (e.g. max. dev. $\pm 0.4\,°$), if the amplitude is changed, and that the rf amplitude per cavity varies less than $\pm 0.25\,\%$, if the phase is adjusted.

CONCLUSION AND OUTLOOK

The experiment successfully demonstrated that the target values, modified by the CEL modules, lead to the desired beam behaviour. According to the bunching level of the beam, the control voltage for the target phase was adjusted with less than $\pm 2.5\,°$ deviation and the relative precision of the control voltage for the target amplitude is $\pm 2.5\,\%$ for the investigated energies from injection up to 600 MeV/u. Thus, the measured actual rf voltages and the calibration strategy[10] are reliable for characterising the influence on the beam. Moreover, a dedicated experiment scenario was presented, which enables the verification of the calibration by a beam observation.

[9]For example, at 600 MeV/u a control voltage of 2 V corresponds to 3.7 kV for BE1 and 3.6 kV for BE2.

[10]For the generation of the calibration curves both rf voltages of the gap halves were taken into account.

In conclusion, the predefined calibration curves clearly fulfil the requirements on the phase and the amplitude accuracy with respect to the beam.
In the next step, the establishment of a series solution for the CELs is planned, which provides the basis for high-precision machine experiments e.g. at multi-harmonic operation.

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