TEST SETUP FOR AUTOMATED BARRIER BUCKET SIGNAL GENERATION*

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Abstract

For sophisticated beam manipulation several ring accelerators at FAIR (Facility for Antiproton and Ion Research) and GSI like the central heavy ion synchrotron SIS100 and the ESR (Experimental Storage Ring) will be equipped with barrier bucket systems. Hence, the associated LLRF (Low-Level Radio Frequency) control has to be applicable to different RF systems, with respect to the cavity layout and the power amplifier used, as well as to variable repetition rates and amplitudes. Since already the first barrier bucket pulse of a long sequence has to meet certain minimum demands, open-loop control on the basis of calibration data is foreseen. Closed-loop control is required to improve the signal quality during a sequence of pulses and to adapt to changing conditions like temperature drifts. A test setup was realized that allows controlling the signal generator, reading out the oscilloscope as well as processing the collected data. Frequency and time domain methods can be implemented to approach the dynamics of the RF system successively and under operating conditions, i.e. generating single sine pulses. The setup and first results from measurements are presented as a step towards automated acquisition of calibration data and iterative improvement of the same.

BACKGROUND

In 1983 isolated bucket RF systems providing a single complete sinusoid gap voltage were for the first time proposed for the Fermilab Antiproton Facility [1]. Related RF considerations modelling the cavities of the AGS (Alternating Gradient Synchrotron) at BNL (Brookhaven National Laboratory) as parallel RLC (resistor, inductor, capacitor) circuits are given in Ref. [2]. This approach was as well followed to successfully generate barrier buckets at the ESR [3] and thereby to enable the demonstration longitudinal stacking with both electron and stochastic cooling [4, 5]. In the examples given up to here ferrite cavities were used for the generation of the single sine gap voltages with the inherent restriction that the cavity's resonant frequency has to match the barrier bucket frequency. For the experiment at the AGS an MA (Magnetic Alloy) loaded cavity was developed by KEK having many advantages over the ferrite loaded cavity. Due to the lower Q-value the required power to generate a single sinusoidal wave becomes much lower [6].

Hence, in 2011 the development of a new MA loaded broadband synchrotron cavity dedicated to barrier bucket operation at ESR was proposed. A prototype system composed of two RF cavity units (1.1 m length & one ceramic gap each) and a broadband solid state amplifier of type AmplifierResearch 1000A225 (10 kHz - 225 MHz, 1 kW) is now available at GSI. Both cavities are mounted in the same housing, but only one pulse per bunch revolution is generated by the same cavity. Details about the design of the cavity and the amplifier selection are given in Ref. [7]. Another barrier bucket system, with a tetrode output stage, is planned for SIS100 [8].

REQUIREMENTS

Both barrier bucket systems should share the same signal generation under development that must thus be applicable to different cavity layouts and power stages used. Barrier bucket operation at ESR is planned for beam accumulation at injection energy and beam compression at lowest energy for extraction whereas at SIS100 it is intended for precompression by means of moving barriers in order to prepare the beam for final bunch rotation. For these purposes variable pulse amplitudes and repetition rates must be supported. Preliminary operational parameters are given in Table 1. Beside the frequency, amplitude and phase variable operation in a wide parameter range is needed. The requested high signal quality of the barrier gap voltage characterizes the challenging project aims. For the SIS100 barrier bucket system the ringing between the pulses is specified not to exceed 2.5% of the pulse amplitude, e.g. to avoid micro-bunching effects. The required amplitude accuracy is 5% [9]. For the first single sine pulse after changing parameters to fulfill the requirements open-loop control on the basis of calibration data is foreseen. To meet the demanding specification with respect to the high signal quality and provide robustness against parameter changes closed-loop control on these calibration data is necessary.

SETUP

The prototype cavity system is driven by a dual-channel waveform generator of the Trueform Series from Keysight Technologies featuring a maximum sample rate of 1 GSamples/s and 120 MHz bandwidth. The output is connected to a DSO (Digital Storage Oscilloscope) from Tektronix with an analogue bandwidth of 500 MHz and up to 5 GSamples/s. A laptop or PC is used to control these

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Table 1: Required Parameters

synchrotron	**ESR**		**SIS100**
operation mode	stacking	compression	–
particle energy	60 - 400 MeV/u	4 MeV/u	80 MeV/u - 3 GeV/u
revolution frequency	0.9 - 2 MHz	250 kHz	110 - 270 kHz
repetition period	0.5 - 1.1 µs	4.0 µs	3.7 - 9.1 µs
min. pulse frequency	5 MHz	1 MHz	1.35 MHz (typ. 1.5 MHz)
max. pulse length	200 ns	1 µs	740 ns (typ. 666 ns)
peak amplitude	1 kV / 2 kV	500 V / 1 kV	15 kV

instruments as well as to collect and process the data allowing automated iterative measurements. The second channel of the AWG (Arbitrary Waveform Generator) set to a CW (Continuous Wave) signal at the repetition rate is used as a trigger for the oscilloscope. This is necessary to obtain comparable measurements with known time coherence and to have the phase of the barrier bucket pulses well-defined as well as adjustable in regard to this reference. The setup is one step towards the given project's objectives, namely the collection and improvement of calibration data, but also provides means to other developments. The communication to the instruments is based on SCPI (Standard Commands for Programmable Instruments) commands and Python code widely used at GSI. The input signal $u(t)$ loaded to the AWG, the measured gap voltage $y(t)$ shown at the DSO, the related Fourier transforms $\underline{U}(\omega)$ and $\underline{Y}(\omega)$ as well as the system's frequency response $\underline{G}(\omega)$ computed according to

$$\underline{Y}(\omega) = \underline{G}(\omega)\underline{U}(\omega) \tag{1}$$

are saved in csv (Comma-Separated Values) file format. Thereby the system behaviour can be approached both by frequency and time domain methods as well as any combinations, e.g. with respect to linear and nonlinear parts of the model.

FIRST RESULTS

Frequency Response of the System

As the overall system consists of several key components even for linear small-signal operation the frequency response is not comparable to the one of an RLC circuit applicable to most ferrite cavities. It was observed that the system's dynamics change considerably over time as shown in Fig. 1. The reasons for and details about this parameter changes are subject of further investigation. To ensure high signal quality the frequency response has to be recorded on a regular basis for instance once per day or extracted from collected data according to Eq. (1), provided that the spectral components have appropriate amplitudes. The acquisition and handling of one data set takes less than two minutes. Until October 2016 the amplitude and phase response of the cavity system was measured by slow sine sweeps in three frequency ranges that took 500 s each. Thus, the tool may replace time consuming measurements of the systems amplitude and phase response.

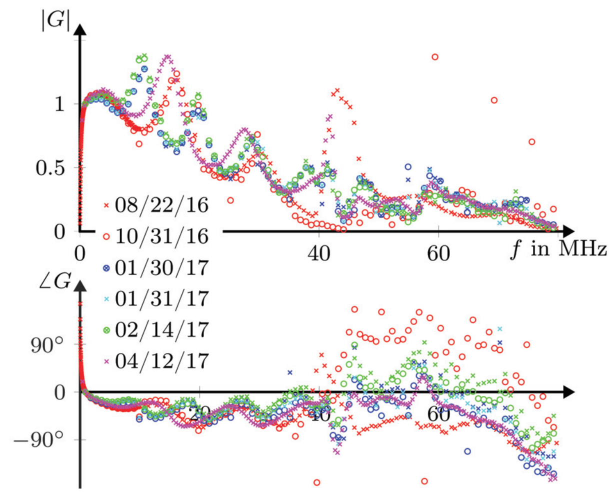

Figure 1: Amplitude and phase response of the test cavity system in the past months.

Calculation of the required input signal by means of the Fourier decomposition and based on the measured frequency response copes with the rather complicated frequency response and moreover allows off-resonance operation rarely realized using the RLC circuit model.

Level Dependent Signal Accuracy

When calculating the required input signal based on the amplitude and phase response of the cavity system the gap voltage reliably meets the specification up to a level of 550 V. At higher signal levels the test cavity system becomes nonlinear especially due to the amplifier.

As a first approach the iteration was performed over the frequency response of the system, i.e. it was recalculated after each measurement according to Eq. (1). It can be seen from the Fourier decomposition $\underline{Y}(\omega)$, even at the limit of the linear region (Fig. 2), that due to the given parameters the 11th frequency component is the first to give trouble. Since 11 is prime, this effect cannot be explained by common harmonic distortion. Even though for much higher amplitudes the signal quality becomes quite poor, this is due to a systematic error. The amplitude and phase of the Fourier transformed gap voltage given in Fig. 3 exemplify the pattern arising from this first iterative approach. Next

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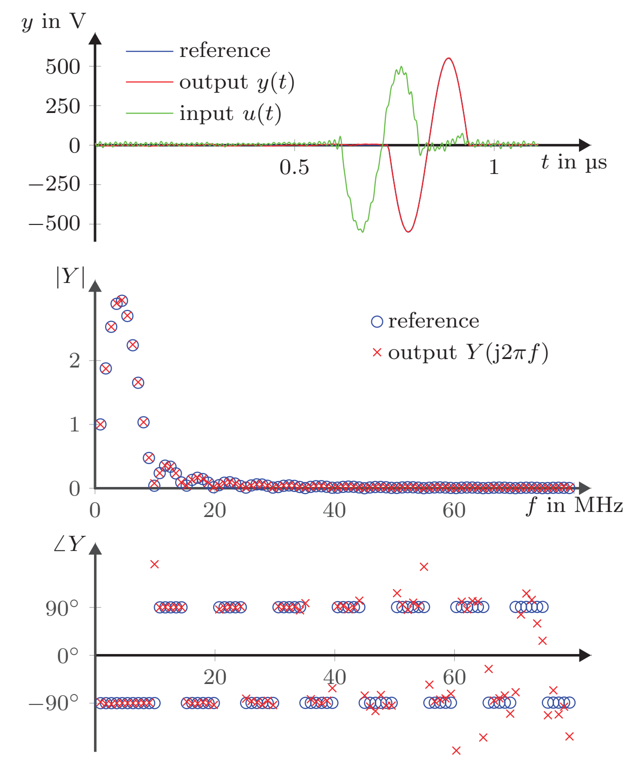

Figure 2: Barrier bucket pulse of 200 ns and 555 V repeated at a rate of 900 kHz meeting the specification [9] with its Fourier decomposition showing noticeable problems in the 11th harmonic.

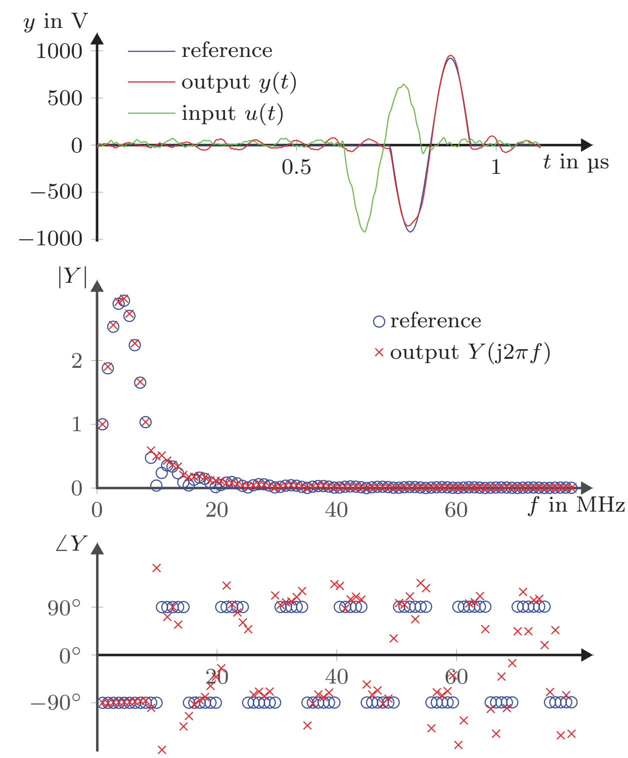

Figure 3: Barrier bucket pulse of 200 ns and 923 V repeated at a rate of 900 kHz with its Fourier decomposition showing a systematic error.

steps include the use of in-phase and quadrature components as well as successive approximation in the time domain [10].

CONCLUSION

Open- and closed-loop LLRF control are necessary to reach high barrier bucket signal quality. As a first step an automated signal generation was implemented recording data from which useful information for calibration can be extracted. Flexible processing of the records is aiming at realizing an active feedback based on measurements acquired during standard operation.

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