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BARRIER BUCKET STUDIES IN THE CERN PS

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Abstract

Part of the residual beam loss during the Multi-Turn Extraction (MTE) of fixed target beams from the CERN Proton Synchrotron (PS) can be attributed to kicker magnets switching while the beam is coasting with the main radio frequency (RF) systems off before extraction. Generating a barrier bucket to deplete the longitudinal line density of the coasting beam during the kicker rise time can reduce these losses. Beam tests have been performed with an existing Finemet® cavity in the PS, which is normally operated as a wide-band feedback kicker. To drive the cavity, a beam synchronous waveform synthesizer based on programmable logic has been developed. It produces a pre-distorted signal which ideally results in a single period sinusoidal voltage pulse with programmable parameters at the gap of the cavity, once or multiple times per revolution. The modelling of the behaviour of the power amplifier and the cavity is essential to achieve an anti-symmetric voltage pulse with little pre- and post-pulse ripple. The design of the beam-synchronous waveform generator is presented together with results from initial beam studies with the created barrier buckets in the PS.

INTRODUCTION

The residual beam losses occurring with the Multi-Turn Extraction [1,2] (MTE) beam can be reduced by generating a gap in the longitudinal beam distribution synchronised with the ejection kickers of the CERN Proton Synchrotron (PS). Such a manipulation requires pulsed radiofrequency (RF) signals to be generated. The wide-band RF system in the PS, which was installed for the coupled bunch feedback consists of a Finemet® cavity [3] and amplifier (see Fig. 1). It has the correct frequency range to be operated as a barrier bucket RF system to generate pulses at the cavity gap. A new low level RF (LLRF) system to create the drive signal has been developed. The first part of the article describes the details of the barrier waveform generation and the LLRF drive implementation. In the second part, the first results with proton beam at injection energy and low beam intensity are presented.

FINEMET® CAVITY AS A BARRIER BUCKET RF SYSTEM

System Description

A beam synchronous direct digital synthesizer (DDS) based on programmable logic (FPGA) drives the six pairs of solid state amplifiers. The outputs of these are directly

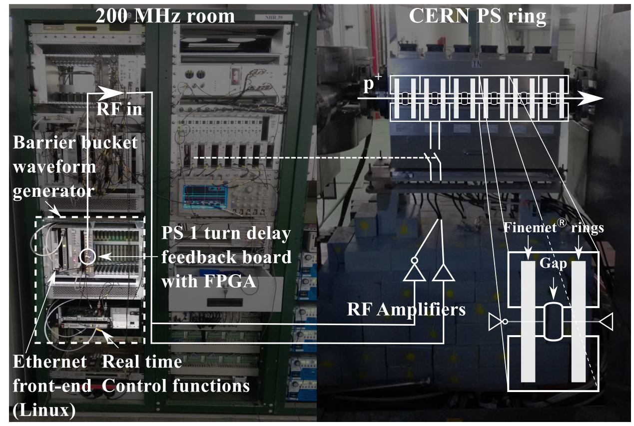

Figure 1: The prototype barrier bucket system as it is installed in the PS.

connected to the cavity gap, see Fig. 1. A dedicated DDS firmware has been developed and a new LLRF installation has been commissioned.

Waveform and Application Requirements

The waveform to produce a barrier bucket consists of a pair of a positive and a negative pulse that are altogether DC free and comparatively short with respect to the revolution period [4]. The sketch in Fig. 2 illustrates such voltages and corresponding RF buckets. Placing two barrier-generating waveforms directly next to each other creates an isolated bucket in between them. Otherwise, the absence of voltage between the pulses yields a barrier bucket.

In addition to these conditions, the application imposes a further restriction on a very important waveform parameter for the beam loss reduction, the pulse duration. This is defined as the time interval when the RF voltage is non-zero (Fig. 2) and is responsible for creating a gap in the coasting beam.

A pulse duration of ≈ 300 ns corresponds to a sufficiently long beam gap extending over the rise time of the kicker. A much larger gap would not achieve further beam loss reduction, therefore this is taken as a maximum value. Moreover, longer gaps are less desirable for the downstream accelerator, since the instantaneous beam current outside the gap region must increase to keep the total intensity constant.

System Model and Waveform Pre-distortion

In order to generate the isolated pulses at the cavity gap, a pre-distortion scheme is needed, since the cavity and amplifier system alters the magnitude and phase of the harmonic components of the input RF waveform.

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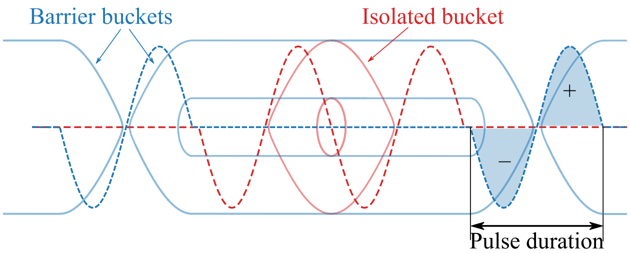

Figure 2: Isolated bucket (red) and barrier bucket (blue) made by moving two RF pulses (dashed) in azimuth. The shape of the waveforms do not have to be sinusoidal as long as they are DC free and the residual voltage is close to zero between them.

A pre-distortion method based on a linear model has been established. The transfer function was measured in frequency domain to determine the steady state response of the cavity and amplifier system. This was complemented by time domain measurements at selected frequencies. The combination of time and frequency domain information allowed to characterise the system transfer function with a higher resolution compared to using the single data sets alone. Therefore, the response could be predicted at a greater precision for all relevant frequencies. Knowing the magnitude and phase shifts the system adds from the drive input to the cavity gap, the inverse of these are calculated. Then the harmonic components of the input waveform are modified accordingly: the magnitudes are pre-scaled and the phases are shifted. Examples of linearly pre-distorted waveforms can be seen in Fig. 3.

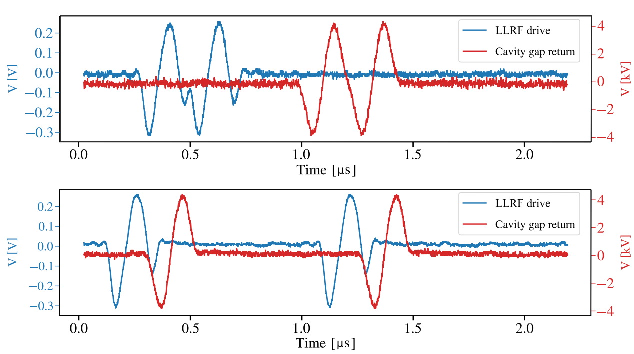

Figure 3: An isolated bucket is created using the pulses in the top plot. The waveform shown in the bottom plot produces a barrier bucket.

The accuracy of the linear model in an open loop configuration does not only depend on the accuracy of the measurements of the system, but also on the non-linearities. Since the system is to be used at peak voltages, tests with sinusoidal inputs of varying amplitude were performed to determine the magnitude of the harmonic distortion at different frequencies. The normalised spectra of the input (Fig. 3) waveforms and the magnitude response can be seen in Fig. 4. Comparing the results of these measurements with the spectrum of the already pre-distorted waveform, it was found that in

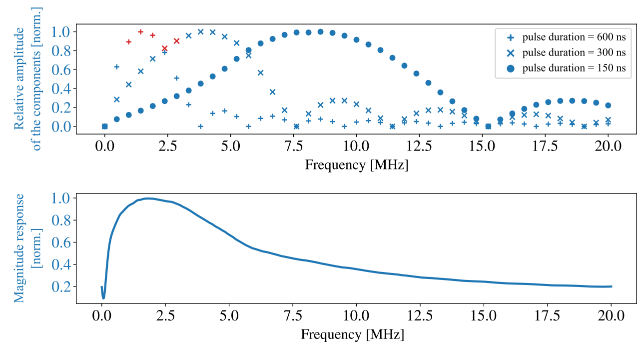

Figure 4: Normalised plots comparing the Fourier spectrum of the pre-distorted barrier waveforms of different widths and the magnitude response of the system. Red markers indicate the parameter region corresponding to harmonic distortion. This occurs when the magnitude of the waveform components coincides with very high amplifier output causing compression. The values were calculated for a revolution frequency corresponding to extraction energy, approximately 476 kHz, but the overall picture is similar at the 10% lower revolution frequency at injection.

the required operational range the system has a nearly linear behaviour.

Limits of the Linear Pre-distortion Scheme

The harmonics generated by the amplifier, in addition to the intended signal at higher harmonics alters the time domain signal. The frequency and amplitude pairs affected by the harmonic distortion are highlighted in Fig. 4. In these cases the asymmetries due to compression are noticeable, and barrier waveforms pre-distorted with a linear scheme will approximate the cavity gap waveform with several percents of error.

A good indicator for the presence of asymmetries is the residual voltage outside the gap region, since in this case the integral of the pulse pair (Fig.2) will not be zero resulting in a tail. Compensating for this required the tuning of the pre-distorted input pulses below the percent level. Test results showed that for longer pulse durations than approximately 300 ns the effect of the amplifier non-linearity became even more apparent at highest amplitudes. An example input spectrum when the imperfections will be dominant is shown in the points corresponding to 600 ns in Fig. 4.

The cavity bandwidth becomes the main limitation for pulse widths lower than 150 ns: the amplitude of the output diminishes.

These lower and upper limitations altogether mean that the present scheme can be used in the foreseen operational conditions to produce gaps from about 150 ns to 300 ns.

Implementation

The barrier bucket waveform generator driving the amplifier and cavity system was implemented on the PS 1-turn delay feedback module [5], which features analogue to digital (ADC) and digital to analogue (DAC) converters and

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an FPGA. Based on this electronic board a new firmware has been developed. Fig. 5 shows the block diagram of the beam synchronous, arbitrary waveform generator. The DDS core [6] provides the beam synchronous azimuth information, Θ, based on the reference clock at 256 times the revolution frequency, f_{rev}. A programmable offset, Θ_{offset}, to change the centre of the generated barrier bucket was added. To create symmetrically moving barriers with respect to the fixed azimuth position, the phase shifts, $\Theta_{\mathrm{barrier}}$, were implemented. Replacing the usual sine look-up tables of a DDS by memories that contain a remotely programmable waveform made it possible to generate the arbitrary, pre-distorted pulses for the given, fixed frequencies of operation. A separate module combines the waveforms preventing the output saturating in case the two pulses overlap using a comparator scheme.

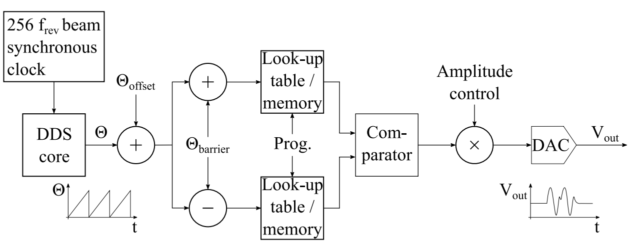

Figure 5: The diagram shows the functional elements of the beam synchronous RF source firmware generating barrier buckets.

VALIDATION WITH BEAM

The beam synchronous source was validated with a low intensity 1×10^{11} protons per pulse (ppp) proton beam at 1.4 GeV kinetic energy. Since the beam induced contribution to the voltage is negligible under these conditions, no compensation for this effect was necessary.

Phase calibration was performed first by varying the azimuth of the injected bunch with respect to the azimuth of the barrier. Only one potential barrier was created per turn. The protons reflecting off both sides of the potential barrier as well as a sketch of the barrier can be seen in Fig. 6.

The next set of tests was performed with moving potential barriers. A series of beam manipulations was performed to match the injected bunch from the PS Booster to the isolated bucket created by the barrier RF system. The beam was kept in this sinusoidal bucket, and then debunched into a barrier bucket (Fig. 2) to observe the longitudinal profile evolution. At $f_{\mathrm{rev}} = 437$ kHz, RF pulses corresponding to an approximately 290 ns pulse duration were made. The resulting longitudinal beam profile evolution can be seen in Fig. 7. The beam was adiabatically debunched between the barriers since the time scale for the beam manipulation seen in Fig. 7 was over 1 s.

However, to achieve a perfectly flat bunch profile at injection energy, making small, empirical corrections to the input waveform corresponding to less than 1% of its peak amplitude was necessary.

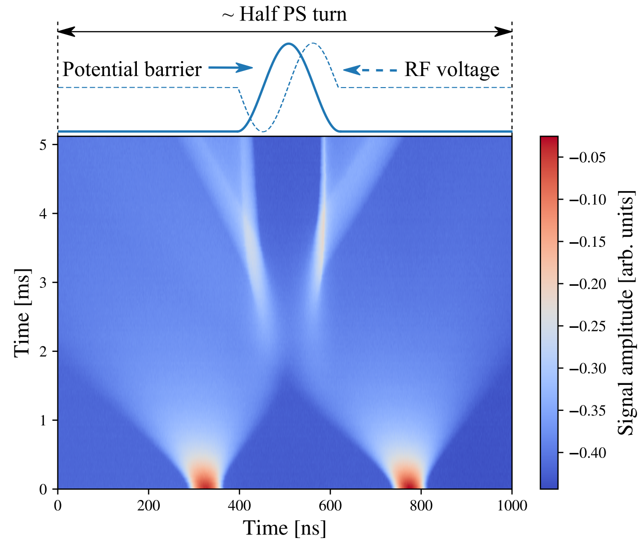

Figure 6: Protons reflecting off the potential barrier in a barrier bucket. Combination of two acquisitions with beam at injection in the PS. The top of the image shows the RF voltage and the corresponding potential.

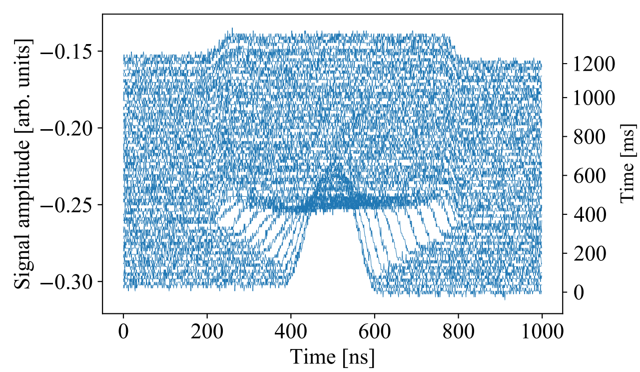

Figure 7: Using the moving barrier feature the beam was debunched into a barrier bucket at 1×10^{11} ppp intensity.

CONCLUSION

A LLRF system was developed for the Finemet® RF system to generate barrier buckets in the PS. A linear waveform pre-distortion scheme was implemented and the installation was commissioned with low intensity beam at injection energy. The first results with beam were presented, where reflections of particles at the potential barrier were observed and the beam was kept in a barrier bucket for about 1 s. The next steps included beam tests at extraction energy and two orders of magnitude higher beam intensities with the results reported in [7].

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