PROTOTYPE RESULTS OF THE ESR BARRIER-BUCKET SYSTEM

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ABSTRACT

The experimental storage ring (ESR) is a synchrotron ring for ions, operated at the GSI facility, Germany. In combination with the existing electron cooler, its acceleration cavities have been used to demonstrate longitudinal beam accumulation in order to increase the beam intensity [1]. Limitations of the existing narrow-band cavities led to the development of a magnetic alloy (MA) based broad-band cavity for the generation of Barrier-Bucket signals. The application of a pre-distortion method demands high linearity of the driver amplifier and highlights the importance of its selection process. In this contribution, the system design is described and data measured at a prototype system is presented.

INTRODUCTION

Accumulation of particles by multiple injections can be made in order to increase the intensity of a particle beam. To create an empty bucket for the next injection and to compress the beam in the existing bucket, two single-sine-wave RF pulses are generated und moved towards each other during subsequent revolutions of the beam. The procedure is shown in Fig. 1.

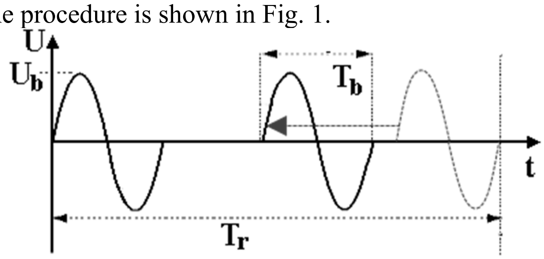

Figure 1: Barrier pulses of duration T_b and amplitude U_b are shifted towards each other to compress the beam revolving with period T_r.

When this procedure is repeatedly applied in combination with beam cooling, high intensities are achieved ("longitudinal stacking"). Desired performance values of the ESR-Barrier-Bucket system are specified in Table 1.

Table 1: System Specifications

quantity		value
U_b	barrier pulse amplitude	>1 kV
T_b	barrier pulse duration	<0.2 µs
T_r	repetition period (ESR revolution period)	>0.5 µs <1.1 µs

PRE-DISTORTION OF SIGNALS

The cavity/amplifier system will have a transfer function $\underline{H}(\omega)$. For linear, time-invariant systems the inverse $H^{-1}(\omega)$ of this transfer function can be used for Fourier analysis in order to determine a pre-distorted input signal, which will produce the desired single-sine RF pulse at the output of the system under consideration. The process employed here is described in [2] and uses the calculation of Fourier series coefficients $\underline{\tilde{c}}_k$ for the input signal from coefficients of the desired signal $\underline{c}_k$

$$\underline{\tilde{c}}_k = \underline{H}^{-1}\underline{c}_k \qquad (1)$$

DESIGN OF THE CAVITY

Each pulse is generated by one cavity box containing one gap and two ring core stacks. To reduce installation length, two cavity boxes were placed in one common housing with a double-gap beam pipe. Each ring core is linked with its own coupling loop, of which four are connected in parallel. The layout is shown in Figs. 2 and 3.

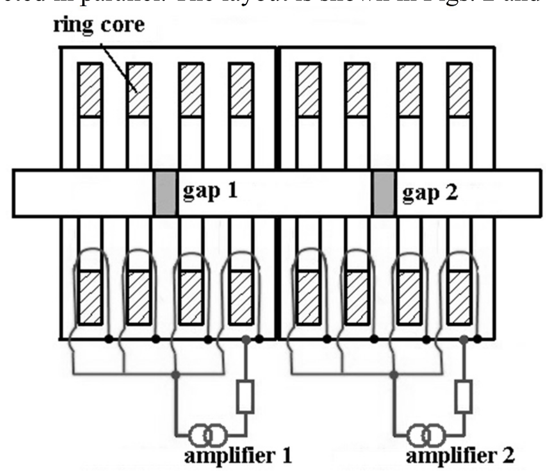

Figure 2: In each cavity box, one RF pulse per revolution is generated. Two cavity boxes share one housing.

The primary design goal is broad-band behaviour of the resonator, therefore ring cores with lowest possible quality factor Q are desired. Iron-based Magnetic Alloy (MA) ring cores of wound-ribbon-type with Q<1 were chosen and an inner diameter d_i=355 mm of the MA material was defined, which allows the installation of beam pipes with a diameter of 250 mm (ESR standard) and CF250 flanges. The ring core thickness h=30 mm was set by availability from the manufacturer.

The cavity´s secondary design goal is impedance matching to the amplifier´s 50 Ω output. From measurements on existing ring cores with the desired impedance, but different geometry the inductance L_{erc}, resistance R_{erc} and complex permeability $\underline{\mu}(\omega)$ were known. Thus, the outer diameter d_o=700 mm resulted from

$$L_{erc} = \frac{\mu_0 \mu_r' h}{2\pi} \ln\left(\frac{d_o}{d_i}\right) \text{ or } R_{erc} = \omega \frac{\mu_0 \mu_r'' h}{2\pi} \ln\left(\frac{d_o}{d_i}\right) \qquad (2)$$

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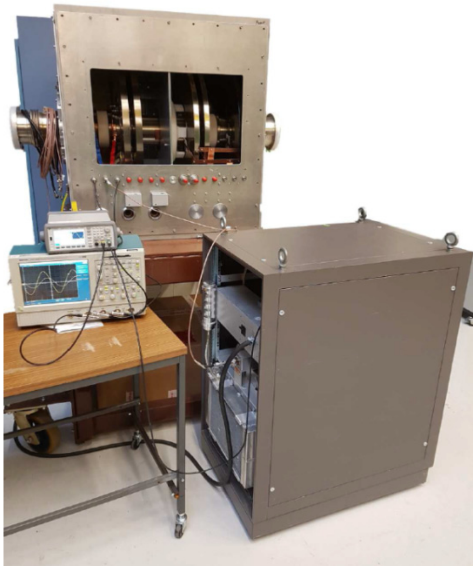

Figure 3: Prototype system with amplifier C.

AMPLIFIER LOAD IMPEDANCE

One cavity box with four ring cores was assembled as a prototype cavity with an available double-gap beam pipe of diameter 150 mm and a housing at hand. The input coupling loops were made from copper sheet metal and the load impedance was measured at the input port of the coupling loops.

This leads to an amplifier load impedance, which is shown in Figs. 4 and 5.

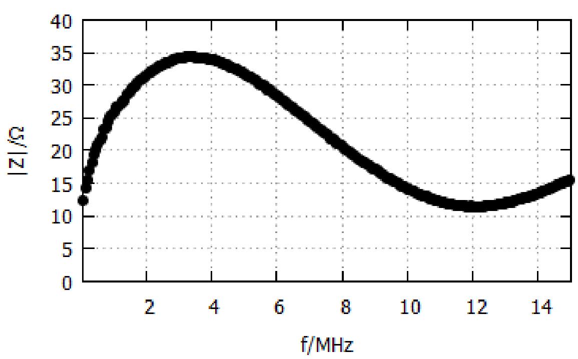

Figure 4: Magnitude of amplifier load impedance Z.

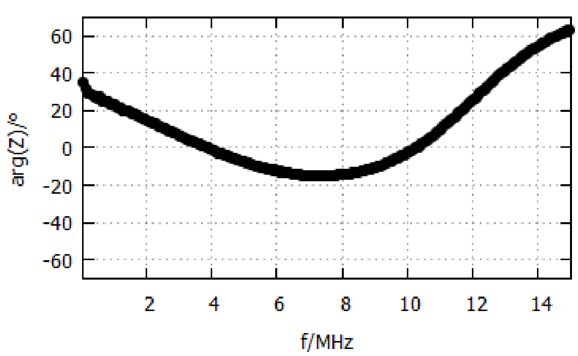

Figure 5: Phase of amplifier load impedance Z.

It might be tempting to suggest the use of only one ring core per stack in order to increase the impedance and improve matching. Unfortunately, this would raise the heat power transferred to each ring core far beyond what can be easily removed with forced air cooling.

AMPLIFIER SELECTION

Two main selection criteria are the amplifier´s capability to work on mismatched loads without damage and suitability for the pre-distortion method used here.

While the first feature is easy to find on the solid-state amplifier market, the latter requires more attention. Since the pre-distortion method used for input signal generation is based on Fourier analysis, it is only valid for linear systems. Hence, the amplifier has to be linear for a large fraction of its input/output voltage characteristic. Unfortunately, no traditional datasheet value represents this fraction for our type of application and manufacturers rarely publish voltage characteristics. Therefore several amplifiers have been tested at the cavity and their voltage characteristic was measured. Figure 6 is a plot of voltage characteristics for three different amplifiers. It shows output voltage as a function of input voltage scaled to input voltage at nominal power. In addition to measurement data, for each amplifier a linear interpolation of the data below 30% is also drawn for comparison.

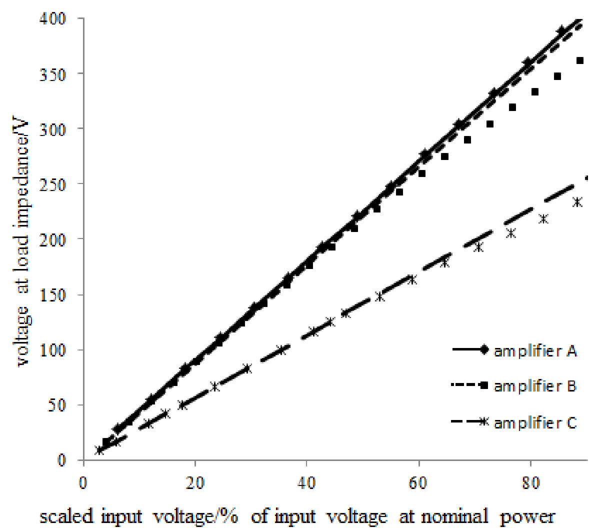

Figure 6: Voltage characteristics for three different amplifiers. Considerable non-linearity is observed for amplifiers B and C, thus only a fraction of their nominal power can be used for generation of Barrier-Bucket pulses with pre-distortion based on Fourier analysis.

Obviously, nominal power alone is not a suitable parameter for amplifier selection, when linearity is needed. Amplifier A remains linear over its full power range up to nominal power, while amplifier B can only be used in applications which require linearity for up to 40% of nominal power. As no other datasheet value contains this information, amplifier selection remains a matter of test and experience. This is emphasized by the fact that Fig. 6 was recorded with pure sine signals as input, whereas complicated signal forms are needed for the application.

Also the amplifier´s required bandwidth can be determined using the Fourier series of the desired single-sine output signal. It will contain non-zero coefficients only for integer multiples of the pulse repetition frequency f_r, which therefore serves as a lower boundary for the amplifier´s bandwidth. Examination of finite Fourier-spectra shows, that the upper boundary needs to be at least 10 times the barrier pulse frequency $f_b=1/T_b$ in order to keep an overshoot at the end of a pulse below 1% of its amplitude. When this is applied to the values of Table 1, a minimum bandwidth of 900 kHz to 50 MHz results. In order to have a considerable safety margin, an amplifier with bandwidth from 9 kHz to 225 MHz and 3 kW nominal power was used for experiments at the prototype cavity system (amplifier A in Fig. 6).

BARRIER-PULSE RESULTS

The system´s transfer function $H(\omega)$ was measured between 20 kHz and 80 MHz. A pre-distorted input signal was calculated for a barrier pulse duration of T_b=0.2 µs (f_b=5 MHz) and repetition period of T_r=1.1 µs (f_r=900 kHz). The input signal was generated and the amplifier´s output power was increased, until visible distortion of the single-sine pulse occurred. In contrast to amplifiers B and C, for amplifier A signal quality remained high for the full power range up to nominal power.

In Fig. 7, the amplifier´s input signal is shown as a jagged line, starting earlier in time than the gap signal (smooth line). The observed barrier pulse amplitude is U_b=1600 V. The signal quality is very good and fulfils the specifications: Overshoot and undershoot at the end of the single-sine pulse have a peak-to-peak amplitude of 2.8% of the pulse amplitude U_b. The negative half-wave´s amplitude exceeds the positive one by about 6.2%, indicating an unwanted offset voltage. This DC-offset probably doesn´t exist at the gap (as the secondary side of a transformer), but is more likely a measurement error.

CONCLUSION

A prototype cavity with magnetic alloy (MA) ring cores can be matched sufficiently to a rugged broadband solid-state amplifier to enable generation of high-voltage (1.6 kV) single-sine pulses. With linear methods of pre-distortion, a high signal quality (ringing after pulse below 2.8%) can be achieved, but only for those fractions of the amplifier´s input/output voltage characteristics, that are linear. While no datasheet value contains this information, nominal power is an incomplete selection criterion and amplifiers have to be tested with regard to linearity.

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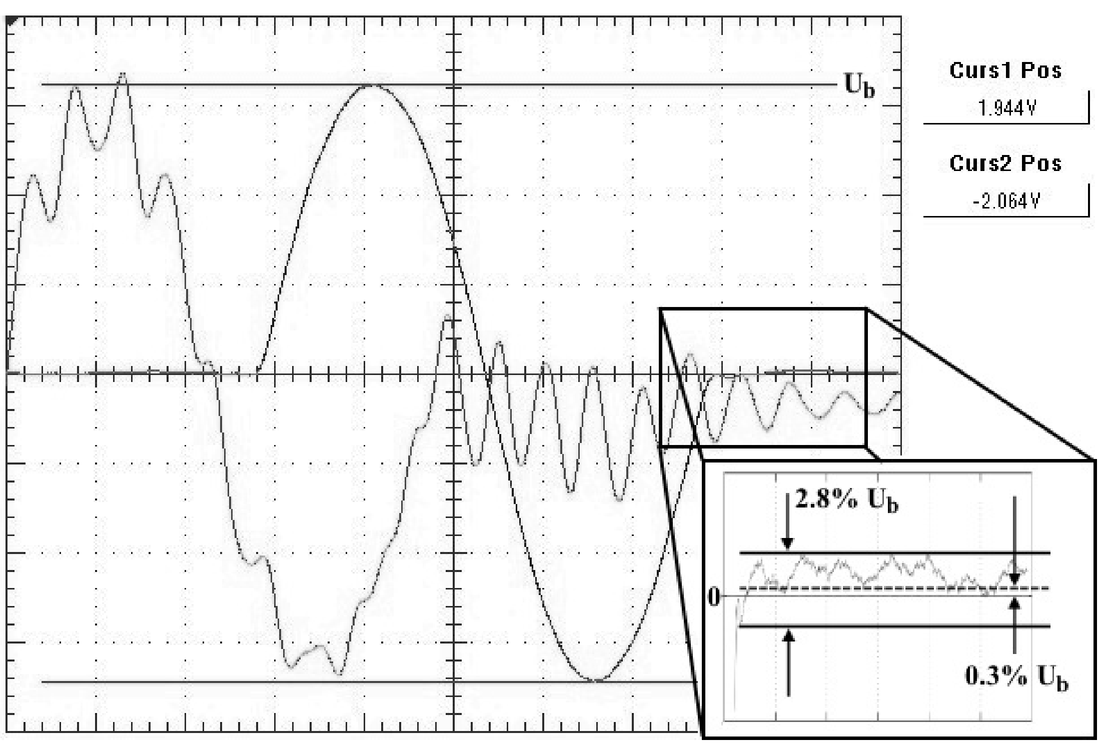

Figure 7: Input signal (jagged line) and single-sine barrier pulse at the output port of a 1:800 gap voltage divider.

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