AMPLITUDE, PHASE AND TEMPERATURE STABILIZATION OF THE ELSA RF SYSTEM

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Abstract

In the stretcher ring of the accelerator facility ELSA electrons are accelerated to a maximum energy of 3.2 GeV applying a fast energy ramp of up to 6 GeV/s. In order to be able to offer higher external beam currents one has to increase the current of the internal beam in ELSA accordingly. The beam current is limited due to excitation of multi bunch instabilities which are mainly caused by higher order modes of the two PETRA cavities used for particle acceleration in the stretcher ring. To control the resonance frequency of these modes, a variable bypass of the cavities' cooling system has been installed which allows a stabilization of their temperature. With this modification, it is possible to vary the temperature of the cavities between 26°C and 65°C and thus to shift the higher order modes by hundreds of kHz in frequency.

Additionally, first operational studies with a prototype of a FPGA based LLRF system (Dimtel) have been performed which in future will be used to stabilize the amplitude and phase of the accelerating RF fields of the cavities.

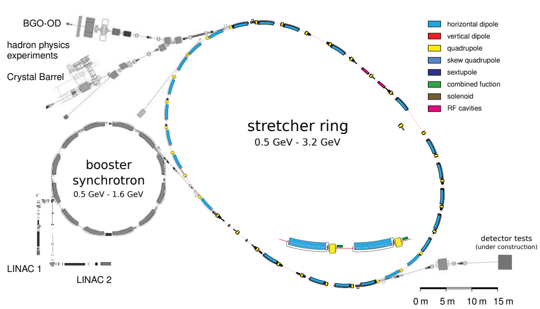

Figure 1: ELSA facility, status 2013.

INTRODUCTION

As illustrated in Figure 1, the **El**ectron **S**tretcher **A**ccelerator ELSA is a three stage electron accelerator. In the first stage, the beam, consisting of either polarized or unpolarized electrons, is accelerated by linear accelerators and then injected into the second accelerating stage, the booster synchrotron. Operating with a cycle of 50 Hz, the booster synchrotron then raises the beam energy to typically 1.2 GeV. The last acceleration stage is the stretcher ring which typically accumulates about 21 injections of the booster synchrotron. Thus, a maximum beam current of 20 mA is reached, the beam is accelerated to energies up to 3.2 GeV applying a fast energy ramp of 6 GeV/s. Then, the beam is slowly extracted to the adjoining hadron physics experiments over a few seconds using resonance extraction methods.

In the framework of the future experimental program, an intensity upgrade of the extracted beam current is planned, requiring an increase of the beam current in the stretcher ring to 200 mA. This increment in intensity is mainly limited by transverse and longitudinal multi bunch instabilities (MBIs). In the longitudinal plane, MBIs are caused by higher order modes (HOM) of the two five-cell 500 MHz PETRA cavities used for particle acceleration in the stretcher ring. The resulting excited coherent beam oscillations (so called multi bunch modes, MBM) are actively damped by three bunch-by-bunch feedback systems, installed in 2010 at ELSA. These systems reduce arising MBI by application of correction signals via transversal and longitudinal kickers, thus increasing the beam current storable in ELSA. For optimal performance of the broadband feedbacks's operation, one has to keep the synchrotron frequency (Ω_s) and the bunches' longitudinal phase (φ) relative to the RF master generator constant. Without control and stabilization of the amplitude and phase of the RF fields in the cavities, these parameters would change due to beam loading effects and energy dependent shifts in Ω_s and φ during the ELSA operation cycle. In order to stabilize these parameters, one has to implement an RF control system capable of performing linear ramps of the cavity voltage and the phase during the fast energy ramp by using feedback and feed-forward techniques. Additionally to the LLRF developments, a system to control cavity temperatures has been introduced at ELSA in order to reduce longitudinal growth rates and improve operational robustness.

AMPLITUDE AND PHASE STABILIZATION

In future, the above outlined stabilization and control will be ensured by a digital FPGA based LLRF system of Dimtel [1]. So far, a prototype of this system has been developed. First tests of its performance were conducted at ELSA in September 2012.

General Layout and DAQ

The prototype version of the LLRF system consists of two LLRF4 boards, which enables the system to acquire six and generate two RF signals. Spartan-3 FPGAs are used for signal acquisition and filtering, interlock functions, real time control and monitoring of the RF signals [2]. A control system interface is provided by an EPICS IOC running under Linux. By using the 500 MHz RF signal of the mas-

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ISBN 978-3-95450-122-9

ter generator (MG), a local oscillator signal at 460.8 MHz is generated. The system is completed by interlock inputs and outputs, trigger and sync distribution. For the data acquisition, each RF signal is downconverted to an intermediate frequency (IF), subsequently sampled by an ADC and then delivered to the FPGA. The FPGA performs real-time field control processing to maintain vector sum probe signals at the desired set point, generating the appropriate klystron drive signal. The setpoints can be dynamically modulated to generate desired amplitude and phase profiles. The FPGA also provides performance monitoring and diagnostic capabilities to the EPICS IOC.

LLRF Component in the ELSA RF System

For testing, the LLRF prototype has been integrated into the ELSA RF system as shown in Fig. 2. A high stability RF reference is provided by the master generator. Prototype inputs have been used to monitor three channels per RF cavity: probe, forward and reflected. Such channel allocation allows the implementation of a tuner control and fast reflection interlocks within the prototype. The 500 MHz drive signal generated by the prototype is boosted by a preamplifier (1). The signal levels were adjusted to reach the klystron saturation point at full-scale DAC output. The amplified signal passes a circulator, and then is symmetrically divided by a magic T (2) and coupled into both PETRA cavities (PC1 and PC2) to be used for particle acceleration.

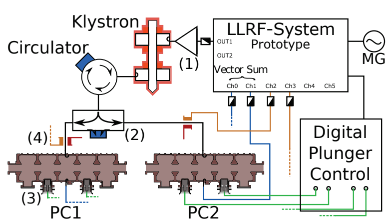

Figure 2: Integration of the LLRF system into the RF system: tuning plungers (3) and directional couplers (4).

Tests with the LLRF System

First function tested was the stabilization of the RF cavities' fields, which rejects beamloading effects and other perturbations and drifts of elements in the RF system. A block diagram is shown in Figure 3. The implementation operates at the IF frequency of 39.2 MHz with 115.2 MHz sampling and uses a non-IQ control method [3]. In open-loop operation, the integrator gain is set to 0 and the proportional gain to unity. The sinusoidal station reference waveform is produced by a CORDIC[1] module from the setpoint amplitude and phase. A reference DDS[2] generator produces an incrementing phase sequence for the CORDIC generator. The RF reference channel (ADC3) is converted to baseband I and Q by a DDC[3]. These cartesian coordinates are converted to polar in real time by another CORDIC. Reference channel phase (measured relative to the DDS phase generator) is subtracted from the station phase drive. This technique allows the system to automatically track the RF reference, rejecting phase noise common to all channels. A vector sum is generated from two cavity probe signals (PC1, PC2) using two-tap FIR gain/phase blocks. In closed loop, the vector sum of two cavity probes is subtracted from the station reference. The resulting error signal is amplified in the proportional and integral channels to generate the klystron drive. The output DAC is updated at twice the ADC rate, so an interpolator is used to upsample the feedback output.

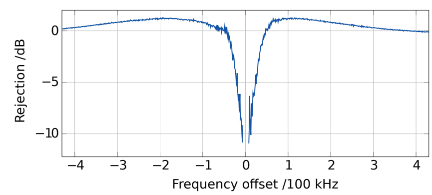

Figure 4: Optimized transfer function to the error point of the closed loop stabilization performance at 30 mA.

The LLRFs feedback loop's capability to reject external perturbations is shown in Figure 4. With static set points, the prototype achieved RF field stability of 0.02 percent and 0.03 degrees (see Fig. 5). Of course one has to note that due to the in-the-loop nature of this measurements, these figures are somewhat optimistic. Figure 6 shows the transfer function at open and closed loop for both cavities.

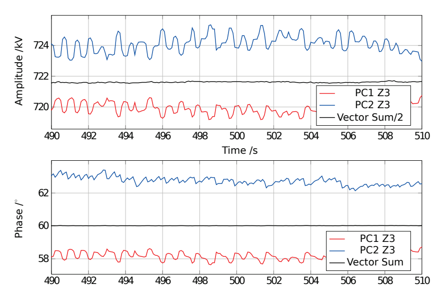

Figure 5: Closed loop performance with static set points.

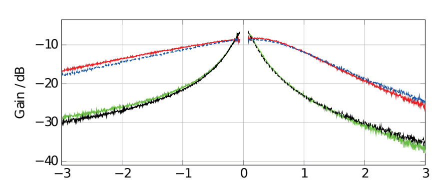

Figure 6: Transfer functions of PC1 open- (green) and closed loop (red), PC2 open- (black) and closed loop (blue).

In order to keep Ω_s and φ constant during the ELSA operation, time dependent set point profiles are used. This allows the system to perform triggered ramping of the cavity

[1] Coordinate rotation digital computer
[2] Direct digital synthesis
[3] Digital downconverter

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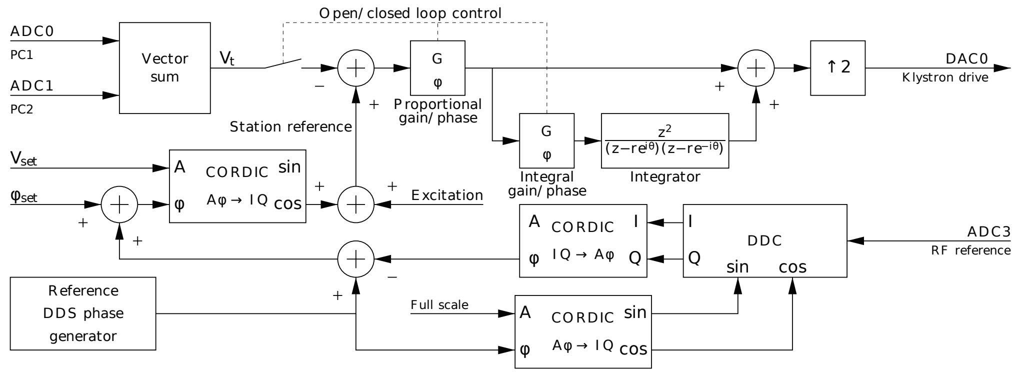

Figure 3: Principle of the LLRF's open/closed loop RF field stabilization.

voltage, e.g. linearly from 250 kV to 725 kV and the field phase from 80° to 60° simultaneously with the energy ramp within 330 ms, obtaining a constant Ω_s and φ. With the development of a digital plunger control, the LLRF system is able to control the cavities tuning plungers thus allowing to implement a tuning and a field balancing loop into the LLRF system. Via a peak detection interlock, the system is also able to perform a rapid shutdown of the RF system in case of exceeding levels of reflected power at the cavities. In near future, the Dimtel LLRF control system, based in part on the prototype, is expected to replace the existing RF control hardware at ELSA.

TEMPERATURE STABILIZATION

An overlap between the impedance spectrum of the PETRA cavities' HOMs consisting of a field of narrow band impedances and the beam spectrum of possible MBMs leads to an instable beam. In order to minimize this overlap, one has to shift the narrow band HOM impedances in the frequency spectrum. This can be achieved by a variation of the temperature of the cavities. Since their resonance frequency is defined by the cavity's geometry, its thermal expansion shifts the HOM frequency. The tuner loops control the frequency of the fundamental mode to maintain minimum reflected power.

Adjustable Bypass

Dissipation of RF power in the cavity results in heating. Therefore, the PETRA cavities are water cooled. In order to enable the cavity temperature control, an adjustable bypass was integrated into the water cooling system separately for each cavity (see Fig. 7). A PID controller adjusts the flow rate of the cooling water through the cavities via three-way valve, which enables cavity temperatures reaching from 27.6 °C to 30.6 °C at klystron powers of 20 kW and from 34 °C to 65 °C, at 180 kW with an accuracy of about 0.5 °C.

Effects of Cavity Temperature Variation

In order to study the effects of a cavity temperature variation on the beam stability, we measured the frequency spectrum via a BPM using the diagnostic capacities of the broad band feedback system. Since every excited MBM corresponds to a sideband in the beam spectrum a distinction between excited and unexcited MBMs is possible. Figure 8 shows the MBM spectrum of a beam of 30 mA at ELSA with an energy of 1.2 GeV at different cavity temperatures. At 32 °C and below, MBM 253 gets excited by a cavity HOM at 1.457 GHz, leading to an unstable beam. Rising the cavities temperature to >34 °C leads to a shifting of HOMs resulting in a more stable beam at this cavity temperature. In future dedicated measurements of the MBIs' temperature dependent growth rates are planned.

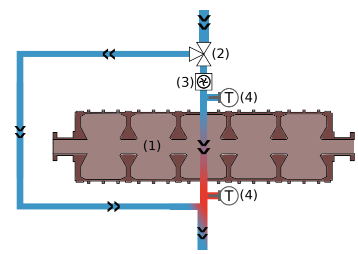

Figure 7: Variable water cooling bypass system of one PETRA cavity (1) with three-way valve (2), flow meter (3) and temperature sensors (4).

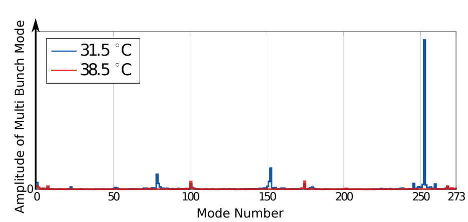

Figure 8: Multi bunch mode spectrum of a 30 mA beam at 1.2 GeV with different temperatures of the cavities.

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ISBN 978-3-95450-122-9