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CONCEPTUAL DESIGN OF THE TRANSVERSE MULTI-BUNCH FEEDBACK FOR THE SYNCHROTRON RADIATION SOURCE PETRA IV

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Abstract

PETRA IV will be a new, fourth-generation, high-brilliance synchrotron radiation source in the hard X-ray range. To keep the emittance low at high beam current an active feedback system to damp transverse multi-bunch instabilities is required. The particular challenge to the system is the very low-noise, while maintaining high bandwidth, which is defined by the 2 ns bunch spacing.

In this paper, we present the conceptual design of the transverse multi-bunch feedback (T-MBFB) system and technical challenges to fulfill the performance requirements. An overview is given on the hardware and the method for detecting and damping the coupled-bunch oscillations. Using modern high-speed ADCs enables direct sampling of pulses from beam pick-ups, which removes the necessity for down-converters. Powerful digital signal processing allows not only for the effective feedback implementation, but also for developing versatile tools for the machine diagnostics.

REQUIREMENTS FOR T-MBFB

The T-MBFB must be able to damp the coupled-bunch oscillations for two PETRA IV operation modes, i.e. brightness mode (maximum 3840 bunches, 2 ns bunch spacing, total current of 200 mA) and timing mode (80 bunches, 96 ns bunch spacing, total current of 80 mA). To suppress the possible oscillation modes, the feedback acts on each bunch (bunch-by-bunch, turn-by-turn system), which requires at least 500 MHz flat magnitude and linear phase detector electronics. The frequencies of the horizontal and vertical betatron oscillations are ~23.4 kHz and ~35.2 kHz, respectively [1].

PETRA IV is planned to have much lower horizontal electron beam emittance (< 20 pm rad in the brightness mode [2]) than PETRA III. The detector resolution must be finer than 1 µm to not degrade the beam emittance [1]. For ± 1 mm expected transverse motion range, the required minimum SNR of the dectector is 60 dB. In a direct sampling detector scheme, the detector noise is dominated by the intrinsic noise of the ADCs, which is discussed later in the subsection on the RFSoC digitizer.

Another requirement is the feedback damping time τ of the multi-bunch instabilities, which was defined to be not worse than 20 turns in any operation mode and for the worst case, i.e. when the synchrotron chromaticity Q' is zero [1]. However, such a damping time is only required for a relatively small transverse oscillation amplitude at the pick-up, i.e. $A_p < 200$ µm.

Additionally, the bunch charge in the timing mode is considerably higher than in the brightness mode, therefore, the MBFB system must have a wide dynamic range and an overvoltage protection to ensure high performance and high reliability for both machine setups.

The T-MBFB requirements and some of the PETRA IV design parameters are summarized in Table 1.

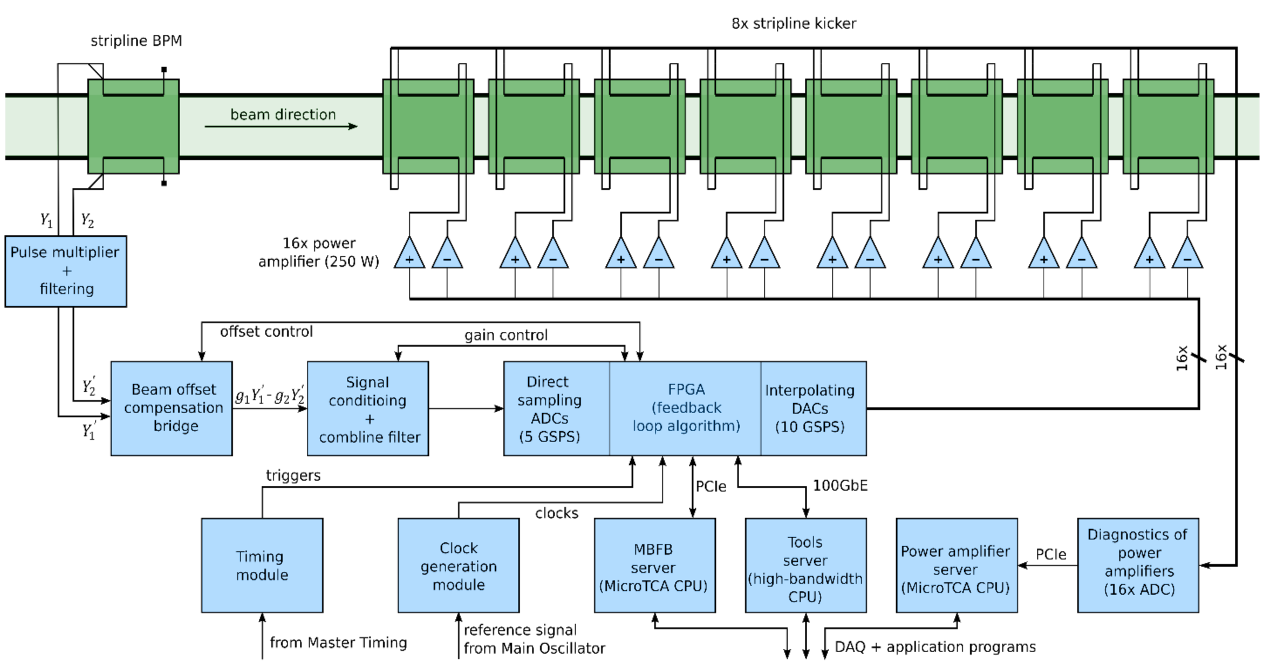

Figure 1: Simplified block diagram of the vertical transverse multi-bunch feedback (T-MBFB).

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Table 1: PETRA IV Design Parameters in the Brightness (**B**) and Timing (**T**) Mode and the Requirements for the T-MBFB

Design Parameter	**Value**
Energy E	6 GeV
Revolution frequency f_{rev}	130.12 kHz
Emittance (ϵ_x / ϵ_y)	< 20 / 4 pm rad (**B**) / < 50 / 10 pm rad (**T**)
Total current I	200 mA (**B**), 80 mA (**T**)
Number of bunches M	max. 3840 (**B**), 80 (**T**)
Bunch current I_b	< 70 µA (**B**), 1 mA (**T**)
Bunch spacing T_{rep}	2 ns (**B**), 96 ns (**T**)
Bunch length σ_t	45.7 ps (**B**), 64.3 ps (**T**)
Betatron freq. (f_x / f_y)	23.4 kHz / 35.2 kHz
T-MBFB det. bandwidth	> 500 MHz
T-MBFB det. resolution	<1 µm at ±1 mm det. range
T-MBFB damping time τ	< 20 turns (A_p < 200 µm)

T-MBFB HARDWARE OVERVIEW

Figure 1 presents a simplified block diagram of the vertical T-MBFB. It is composed of a stripline BPM, a series of stripline kickers and a feedback controller electronics. In the following subsections, the particular components are treated in more detail.

Stripline BPM, Pulse Multiplier and Filtering

Stripline BPM is composed of four electrodes (stripline pick-ups) equally distributed around the beam pipe, i.e. every 90°, with a characteristic impedance Z_0 of 50 Ω. For the vertical beam position measurement, electrical pulses from the upper and lower pick-ups are combined together, creating signals Y_1 and Y_2 (Fig. 1), respectively. For the horizontal beam position measurement, the left and right pick-ups are combined.

The pick-up transfer function is mainly defined by the electrode length L and the electrode width α [3, 4]. The electrode length was selected to be 7.5 cm resulting in the maximum transfer function at 1 GHz and a relatively flat magnitude in the range from 750 MHz up to 1250 MHz, i.e. the frequency band used for the transverse oscillation modes detection. The electromagnetic simulations show that the electrode width α of about 34° is optimal regarding the coupled-out signal power and the characteristic impedance matching [5]. The vertical and horizontal BPMs are located at high beta $\beta_{\mathrm{p,ver}}$ and $\beta_{\mathrm{p,hor}}$ position in the ring, respectively, to improve the detector resolution.

Figure 2 shows the analog signal processing of a pulse after it is coupled out from the pick-up. Firstly, it is delivered to a pulse multiplier, i.e. a passive device composed with a 2-way power splitter, two coaxial cables differing in the electrical length by 1 ns and a 2-way power combiner. It improves the detector resolution by 3 dB, because twice more samples can be used for the pulse amplitude detection.

In the next step, the multiplied pulse is filtered with a 6-pole, lowpass, 2 GHz bandwidth, Bessel filter. Due to linear phase response of the filter, it does not produce any ringing overlapping the next bunch. After lowpass filtering, the signal is provided to the beam offset compensation bridge.

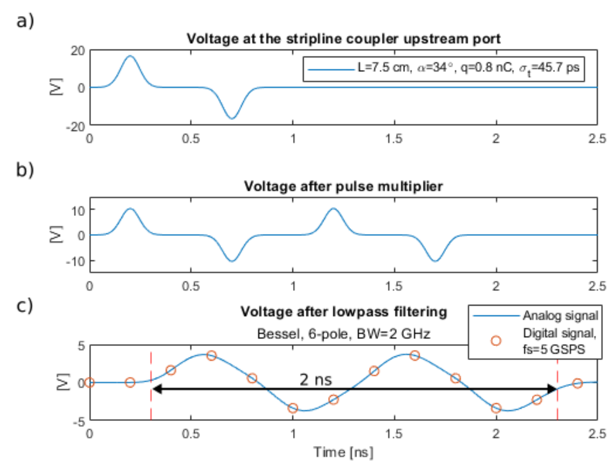

Figure 2: a) Voltage at the stripline coupler upstream port for the electrode length L=7.5 cm, electrode width α=34°, bunch charge of 0.8 nC and Gaussian bunch duration of 45.7 ps in the brightness mode, b) voltage after using the pulse multiplier, c) voltage after applying the 6-pole, lowpass, 2 GHz bandwidth, Bessel filter and a digital signal with a 5 GSPS RFSoC digitizer.

Beam Offset Compensation Bridge and Combline Filter

The in-phase signals Y_1' and Y_2' (Fig. 1) are conditioned to have the same amplitude using variable attenuators and further they are subtracted from each other using a wideband RF transformer. This circuitry is called beam offset compensation bridge (BOCB) and it is used to make the detector only sensitive to transverse beam oscillations, not to the absolute beam position in the vacuum chamber or to the uneven bunch filling.

In the frequency domain, the BOCB suppresses the bunch repetition harmonics and the revolution harmonics, which are associated to the set of frequencies [6]

$$f = pf_{rep} \pm mf_{rev}, \quad (1)$$

where p is the integer number ($-\infty < p < +\infty$), f_{rep} is the bunch repetition frequency, m = 0, 1, …, M-1 (M bunches equally spaced) and f_{rev} is the revolution frequency. The suppression of the above harmonics by more than 30 dB protects the electronics from saturation and increases the measurement resolution, because it allows to use almost full-scale of the ADCs for the betatron signal oscillation. The BOCB for the horizontal and vertical planes are implemented on a single MicroTCA module called DRTM-MBFB-CSI (Fig. 3).

Optionally, the harmonics suppression can be further increased by a combline filter connected in series with the BOCB. The filter is constructed using a delay line based on the fiber-optic technology.

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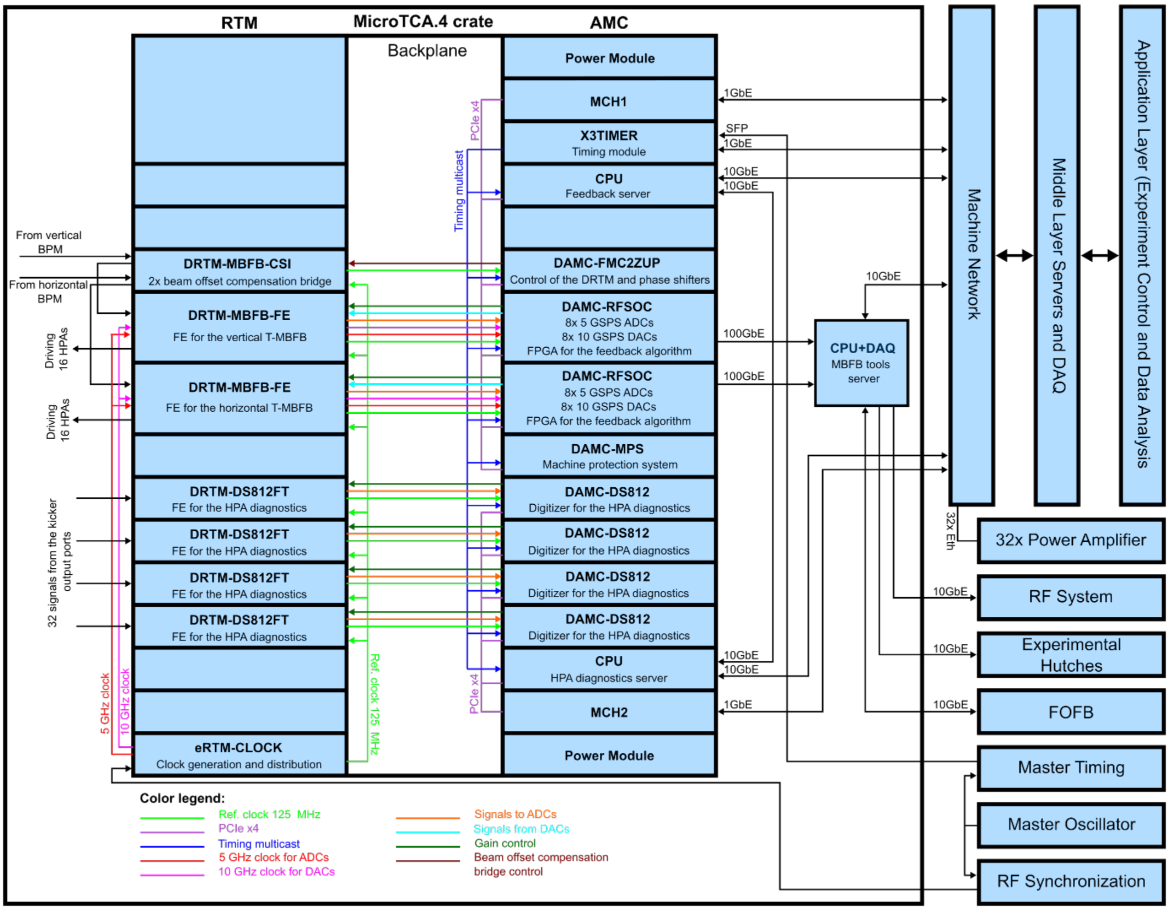

Figure 3: Implementation of the T-MBFB in the MicroTCA .4 form factor and interfaces to the control system, DAQ and various PETRA IV subsystems.

Zynq UltraScale+ RFSoC Integrating RF-ADCs, RF-DACs and FPGA

Advance in ADC technology allows for direct conversion of RF signals to the digital domain without using any analog down-converters. The signal from the BOCB (DRTM-MBFB-CSI) is fed to the ADC front-end module (DRTM-MBFB-FE), which includes a chain of RF amplifiers and variable attenuators to provide the high dynamic range required for the various machine operation modes. The conditioned signals are transmitted over Zone 3 connector to the AMC module DAMC-RFSOC. This module includes the Xillinx Zynq UltraScale+ RFSoC, a platform that integrates eight ADCs (14 bit, 5 GSPS), eight DACs (14 bit, 10 GSPS), processing resources (FPGA, APUs, RPUs) and various fast communication interfaces like 100GbE or PCIe. The MBFB system uses two DAMC-RFSOC modules, one for the horizonal and one for the vertical feedback (Fig. 3).

Resolution of the T-MBFB detector is limited by noise and spurs of the ADC. SNR of the ADC for a single pulse amplitude measurement with a 250 MHz bandwidth averaging filter is equal to about 62 dB, which is only a few dB more than specified in the PETRA IV requirements. However, it is improved by using the pulse multiplier (+3 dB in the brightness mode) and by simultaneous amplitude measurement with N parallel ADCs ($+10\log_{10}N$ dB). It is planned to use 4 ADCs for the feedback, which yielding a final detector SNR of about 71 dB.

After converting the analog pulses to the digital domain, the FPGA is used for the digital signal processing. The calculated kick values are streamed every 2 ns to eight, differential output DACs, which drive 16 high power amplifiers, i.e. one differential DAC is used for one stripline kicker (each electrode of the kicker is driven with the opposite polarization).

Stripline Kickers and Damping Time

The stripline kickers must reliably act upon every single bunch to damp the betatron oscillations. In a storage ring with 500 MHz bunch repetition rate (max. possible with given RF cavity frequency for PETRAIV), the decay time of the electromagnetic field inside the kicker has to be less than 2 ns in order to avoid the following bunch being affected. Additionally, the kicking strength, expressed as the shunt impedance R_s, should be maximized over the full spectrum from DC to 250 MHz.

Based on the formula for the ideal cylindrical stripline kicker given in the reference [7], the stripline length L was selected to be 30 cm, which provides relatively flat shunt impedance up to 250 MHz and zero shunt impedance at multiplies of 500 MHz what considerably reduces beam energy coupling out to the kicker load (see Fig. 4).

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Figure 5 shows the damping time constant versus oscillation amplitude at the BPM calculated for the system with eight stripline kickers driven with the total electrical power P_t of 2.8 kW. The kicker shunt impedance was assumed to be 3.4 kΩ, which is the worst-case scenario, i.e. the fastest mode at 250 MHz. Damping time constant is lower than 20 turns for any operation mode and for $A_p < 258$ µm, which meets the T-MBFB requirements. The horizontal and vertical kickers are placed at high beta $\beta_{\mathrm{k,hor}}$ and $\beta_{\mathrm{k,ver}}$ locations.

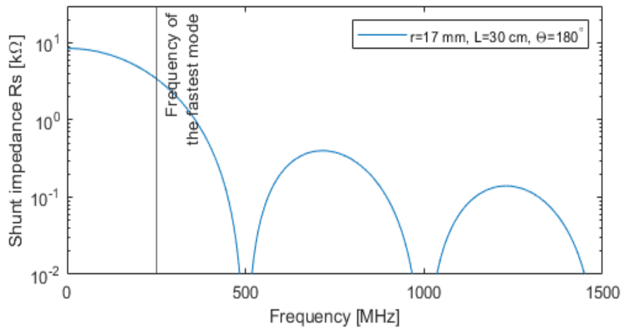

Figure 4: Shunt impedance of an ideal stripline kicker for the length L of 30 cm, the radius r of 17 mm and the opening angle of the striplines θ of 180°.

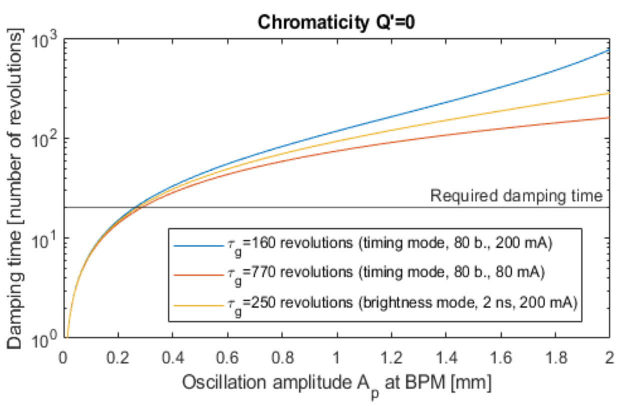

Figure 5: Damping time constant vs. oscillation amplitude A_p at BPM and for various growth rate time constants τ_g. The calculations are based on the following parameters: R_s=3.4 kΩ, P_t=2.8 kW, β_{BPM}=35 m, β_{kicker}=45 m.

Timing and System Clock

The main oscillator of ~500 MHz provides the reference signal to the master timing system and for RF synchronization. The RF synchronization distributes the reference signal to the eRTM-CLOCK, which generates low phase-noise 5 GHz and 10 GHz clocks for the feedback ADCs and DACs. The eRTM-CLOCK includes also a voltage-controlled phase shifter that compensates phase drifts of the RF synchronization in relation to the bunch phase.

The master timing multicasts data to the remote receivers (X3Timer) including a variety of information. The most critical are the revolution trigger and the absolute time with high resolution to time stamp various events. X3Timer distributes triggers and information data over AMC backplane to all AMC modules.

Redundancy

Mean time between failures (MTBF) of PETRA IV is a crucial parameter. In case of any component malfunction, the T-MBFB should be immediately brought back into operation. Therefore, the critical modules are made redundant so that the failures not lead to beam loss or in case of beam loss machine operators can restart the system promptly.

CONCLUSION

The concept of the T-MBFB hardware for the synchrotron radiation source PETRA IV has been developed. The envisioned design would fulfill the demanding performance requirements for detecting and damping high-bandwidth, coupled-bunch oscillations with enough resolution to not degrade the bunch emittance. RF-ADCs are used for the direct sampling of broadband pulses, which simplifies the analog design by omitting the down-conversion stage.

The feedback electronics is based on the MicroTCA.4 form factor that offers modularity, redundancy and availability of some commercial modules which reduces the development cost. The hardware structure gives flexibility for future upgrades and for the installation of additional modules in case any performance improvement is required.

In this paper, we have not reported any analysis of the MBFB algorithm, its implementation in the FPGA (firmware), diagnostic tools, DAQ and control system, which currently is in the design stage. The hardware provides powerful processing resources and high-speed communication interfaces, therefore, it can be flexibly used for various demanding firmware and software needs.

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