NEW DESIGN OF HIGH ORDER MODES ELECTRONICS IN MTCA.4 STANDARD FOR FLASH AND THE EUROPEAN XFEL

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Abstract

At free-electron linear accelerators, various High Order Modes (HOM) - both monopole and dipole - are excited. Extensive studies at DESY have shown that monitoring and analysis of some of these modes can be used for different applications including Beam Position Monitors (BPMs) and the reduction of wake-fields, the measurement of the beam phase with-respect-to RF signal in cavities, and the measurement of cavity alignment in the 1.3 GHz cryo-modules. Three frequencies were chosen for further experiments: the 1.3 GHz base frequency from the klystron, the 1.7 GHz dipole mode and the 2.4 GHz monopole mode. In order to realize the monitoring and analysis requirements, very high resolution measurements in amplitude, phase and shape (time resolution) are required for all three frequencies simultaneously. In this paper, we present the new HOM electronics prototype including a microstrip and stripline RF tri-passband filter design and measurements and the specialized MTCA.4 Rear Transition Module for HOM measurements with an ultra-fast high-resolution AMC digitizer.

INTRODUCTION

At modern free-electron linear accelerators, like the FLASH[1] and XFEL[2] at DESY in Hamburg, a high performance electron beam is accelerated in superconducting cavities. This beam causes various High Order Modes to be excited inside the cavities. Extensive studies at DESY have shown that some of these modes can be measured and analyzed for different purposes and applications. Among these applications are: Beam Position Monitors (BPMs) and the reduction of wake-fields, the measurement of the beam phase with-respect-to RF signal in cavities, and the measurement of cavity alignment in the 1.3 GHz cryo-modules.

HOM MEASUREMENTS IN SC CAVITIES

The HOM-based beam monitors transform beam excited Higher Order Modes in the superconducting cavities into information about the transverse beam position and phase. For the measurement of beam position, a dipole mode at 1.7 GHz is filtered out of the spectrum, with a bandwidth of 20 MHz. This is one of several modes with the highest R/Q, i.e. higher interaction with the beam, therefore giving signals with higher power and, as a result, better resolution. The amplitude of this mode is proportional to the offset from the cavity center of the bunch which excited it, therefore enabling the beam position measurement. The signal has to be normalized to the bunch charge. Monitoring dipole fields also enables the alignment of the beam in the cavity center. This leads to reducing the transverse wakefields, which are the sum of all transverse modes, and therefore reducing their negative impact on the beam quality.

The current electronics for beam alignment and position measurement has been installed at 40 cavities in FLASH[3]. A mode around 1.7 GHz is filtered, downmixed to 20 MHz and then digitized with a 108 MHz clock. The raw HOM signals are used for operation, particularly for beam alignment during commissioning phases of the accelerator. When used for beam position monitoring, a single bunch resolution below 10 μm rms has been shown. HOM-based beam position monitors for 3.9 GHz superconducting cavities have been also investigated at FLASH[4] and are being planned for the XFEL [5] However all those monitors have the problem of unstable calibration. While the reason is not yet fully clear, one cause may be phase drifts in the LO generation.

For phase measurement a higher order monopole mode at 2.4 GHz is filtered out of the HOM spectrum, together with the 1.3 GHz accelerating field. In the classical phase measurement one measures the beam excited and the accelerating field, both at 1.3 GHz. Therefore somewhat higher charges are needed, in order to distinguish the beam excited signal from the strong accelerating field. When monitoring a monopole mode at a higher frequency, the signals can be easily separated. Therefore this would also allow the permanent monitoring of the beam phase with respect to the RF and therefore be used by the LLRF for phase regulation. A proof-of-principle of this method has been made using a broadband scope[6]. A resolution of 0.1 deg over a short time has been observed.

DIRECT SAMPLING USING UNDERSAMPLING

The standard HOM measurements all involve the process of downconversion, which introduce many problems and drawbacks into the measurement systems. Of these problems there is need for complex LO generation which can introduce big drifts in the system as well as non-linearities characterizing analog mixers. The solution for these problems is the use of direct sampling in the measurement systems. Modern technology advancements have resulted in the possibility of using very high-speed ADCs (~1GSPS)

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with large input bandwidths (~3GHz) for sampling RF analog signals.

Even though the signal frequencies of the HOM systems are much higher than the Nyquist bandwidth of the ADCs, direct sampling can be used along with the undersampling technique[7]. Using this technique, the measured signals are seen shifted to the first Nyquist zone in the frequency domain (fig. 1). This technique can be used as long as the sampling frequency is higher than two times the bandwidth of the input signal, and not the actual frequency. Information about this frequency is lost during the process, but the amplitude phase and shape[1] of the signal are preserved which is enough for the HOM measurements.

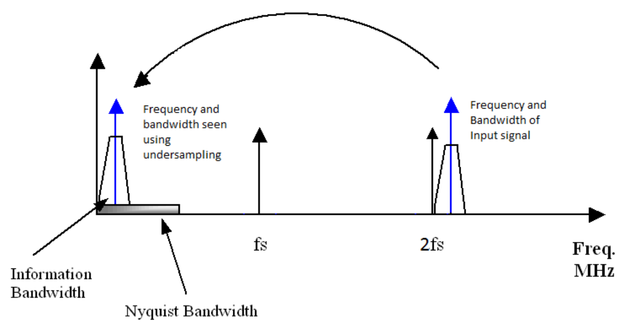

Figure 1: Harmonics moved to first Nyquist Bandwidth due to undersampling.

SYSTEM CONCEPT

The new system design concept implements monitoring and measuring the amplitude, phase and shape of three different frequencies using direct sampling. The frequencies are 1.3 GHz, 1.7 GHz, and 2.4 GHz. The measurement system concept can be broken down to single HOM measurement channels. Each HOM channel measures all three signals simultaneously.

HOM Measurement Channels

Each HOM channel consists of a specialized HOM filter, signal conditioning circuits and a high speed ADC. The block diagram of a single channel is shown on Fig. 2.

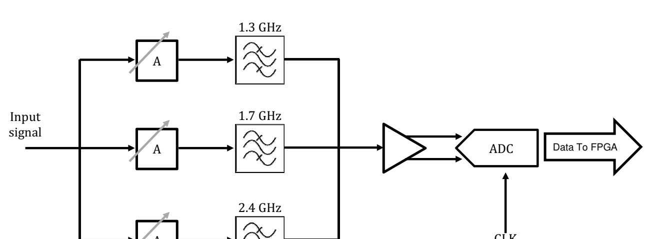

Figure 2: Single HOM ADC channel.

[1]in the frequency domain.

HOM Filter Design The signals for the HOM modules from couplers at the accelerator are a wide spectrum of different frequencies (Fig. 3), out of which only three are interesting for the HOM-based measurements. Moreover, relative measurements are crucial between the frequencies.

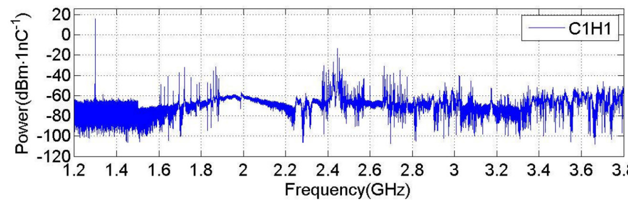

Figure 3: Example full spectrum from coupler.

A special state-of-the-art tri-bandpass filter was specially designed for the system. The filter combines microstrip and stripline design that is implemented directly on the PCB in order to optimize the occupied space in addition to filter parameters. The filter is made of three sub-filters, each for a single frequency that are combined in a special design. Figure 4 shows the filter implemented in two PCB layers seperated by a ground reference. The transmittance and matching of the design is shown on Fig. 5 while Fig. 6 shows the prototype PCB 3D model.

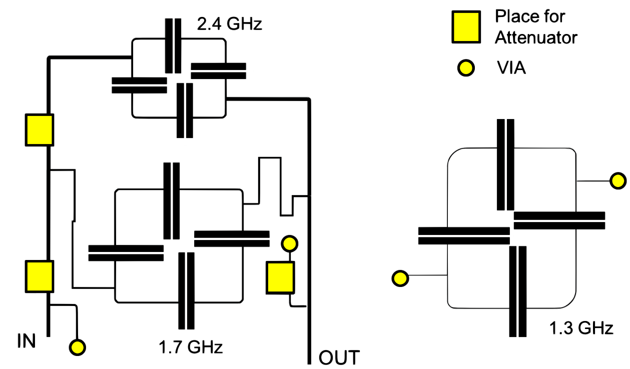

Figure 4: Filter design (left part is a microstrip, right is a stripline below the first part).

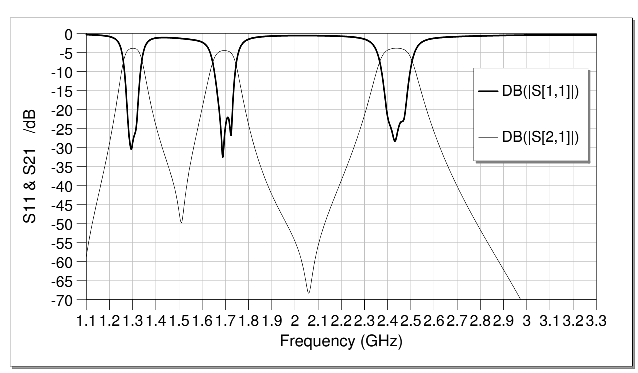

Figure 5: HOM filter spectrum.

The three frequencies, as stated before, are the 1.3 GHz with a 37 MHz BW, 1,7 GHz with a 54 MHz BW and a 2.4-2.74 GHz BW as can be seen on Fig. 5.

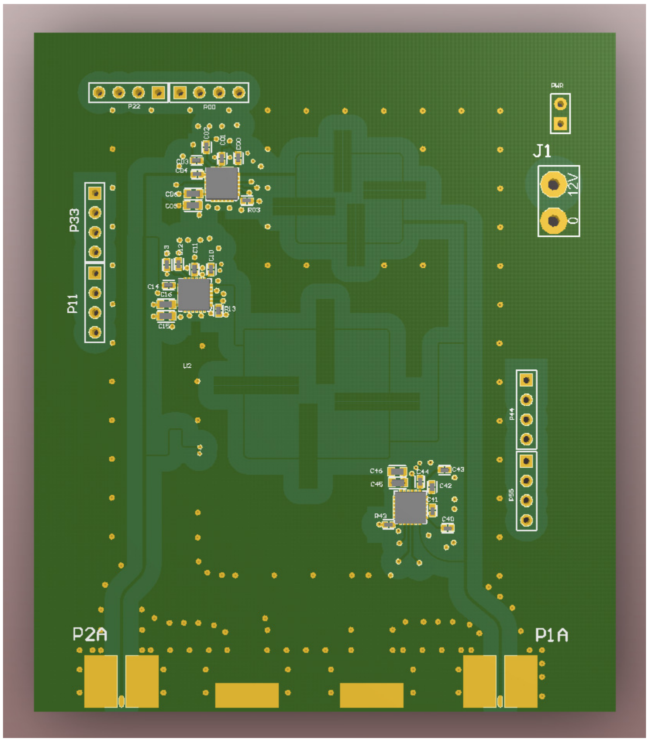

Figure 6: HOM filter prototype.

High Speed ADCs with Matching Circuits The three signals in one channel have different RF power so in order to maximize ADC performance and individual attenuators are implemented for each frequency. The three signals are then combined, the result amplified and differentiated to be fed to an ADC. All connections must be carefully matched to insure proper RF operation in a wide bandwidth.

ADC Clock Frequency Using undersampling for the measurements is benefiting from the aliasing phenomenon. The different frequencies are shifted to the first Nyquist zone. The shifted frequency is a result similar to mixing with the ADC clock frequency. Thus, the frequency must be carefully chosen such that the shifted signals do not overlap in the spectrum. Moreover, the frequency must be generated using the 1.3 GHz coming from the accelerator's Master Oscillator, without introducing too much clock jitter. This frequency calculated for the HOM measurements is 660 MHz.

MTCA.4 HOM Measurement Modules for FLASH and the European XFEL

As stated before, the HOM measurement systems using the downconversion scheme in the VME standard are already installed in FLASH accelerator at DESY. An upgrade to the MTCA.4 is forseen to be compliant with the new overall system of the accelerator. Moreover, the new improved HOM modules are to be installed in the XFEL accelerator (Fig. 7):

- The injector (I1) requires 16 HOM ADC channels i.e. 2 modules,
- the first sector of the LINAC (L1) requires 32 channels i.e. 4 modules,
- the second sector (L2) requires 48 channels i.e. 6 modules,
- the third sector (L3) requires 384 channels i.e. 48 modules.

This results in 60 HOM measurement modules required for the XFEL accelerator, which gives 480 channels. A single module for the HOM measurements consists of two cards in the MTCA.4[8] standard: an ultra-fast high-resolution digitizer and a specialized HOM-filter card with analog front-end circuits and clock generation. Figure 8 shows the main boards of the XFEL MTCA.4 crate with two HOM modules.

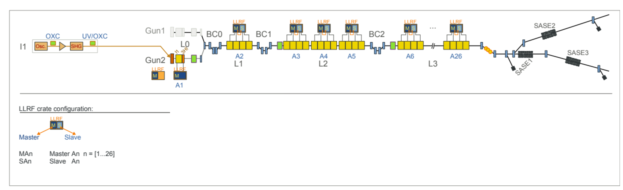

Figure 7: XFEL accelerator block diagram with 4 major sectors and MTCA.4 crates.

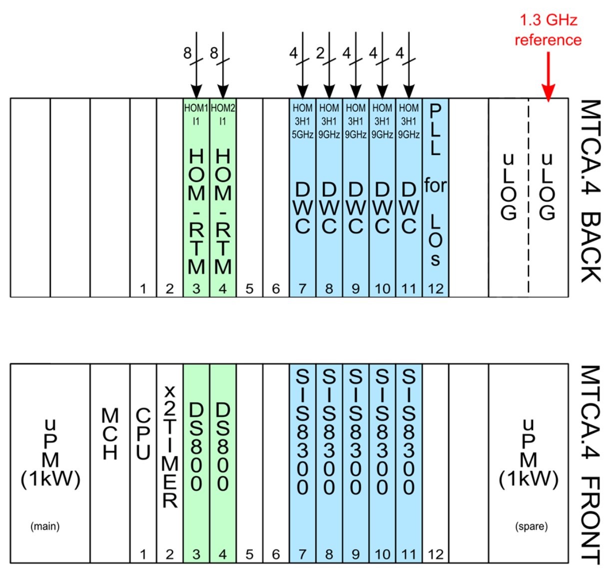

Figure 8: MTCA.4 crate diagram with HOM modules.

Fast Digitizer Card The fast digitizer named DAMC-DS800 developed at DESY is an Advanced Mezzanine Card (AMC) compliant with the MTCA.4 standard and following the analog A1.1 class design recommendation. It holds eight very high speed ADCs that can sample RF signals of frequencies up to 2.7 GHz with sampling rates up to 800 MSPS. It contains a very powerfull Xilinx Virtex 6 FPGA that can handle data from all eight ADCs with the maximum sampling rate, as well as all other circuits and processes on the board. Among these processes is the acquisition of the gathered data in implemented high speed SRAM modules that can hold up to 4MS of data from each ADC channels[2]. The saved data can then be used for future analysis of the HOM measurements. Even though the board implements a low-noise clock distribution circuit, for optimal performance ADC clock generation and distribution for the HOM measurement system will be done on the RTM module. The board is shown on Fig. 9.

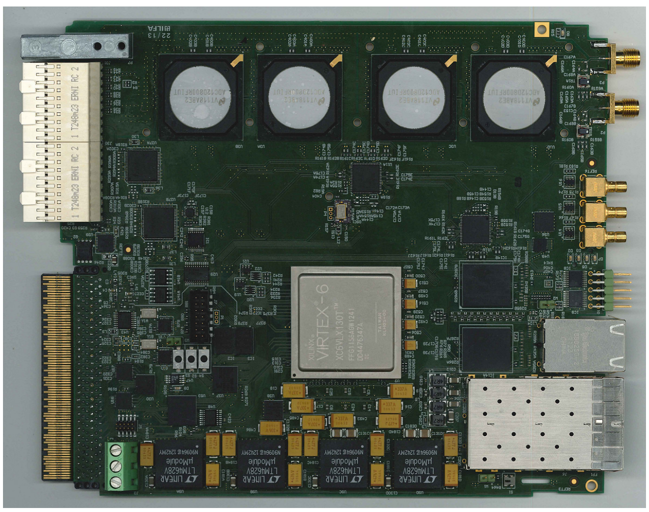

Figure 9: DAMC-DS800 MTCA.4 Fast Digitizer.

Specialized HOM RTM The specialized module for the HOM system, also developed at DESY, is a Rear Transition Module (RTM) named DRTM-HOM and is also compliant with the MTCA.4 standard and following the analog A1.1 class design recommendation. Thus, it can be paired with the DAMC-DS800 digitizer and or other digitizer boards compliant with the standard. The RTM would consist of eight of the specially designed tri-bandpass filters to isolate the frequencies required for the HOM measurements. It also holds very low noise clock genetration and distribution circuits for the ADCs as well as synchronization of the digital parts of the AMC card.

SUMMARY

A new HOM measurement system is being designed and implemented at the DESY accelerators FLASH and XFEL. It is prepared in the MTCA.4 standard, and involves a very high-speed digitizer and a specialized RTM module. The design uses direct sampling for data acquisition, so no complex LO nor downconversion is needed. This process would eliminate problems with LO drifts and nonlinearities resulting from downconversion, as well as simplify the construction of the electronics system. The construction of the system involves state-of-the-art design techniques in all aspects of modern electronics, from specialized analog RF, to ultra fast analog-to-digital conversion and very low noise clock distribution, in addition to high speed digital circuits. The next steps would be to measure and tune the single modules of the system and install them in the accelerators for live HOM signal measurements.

[2] SRAM blocks from 512 KS/channel to 4MS/channel can be assembled depending on the needed variant

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