

# RF ELECTRONICS FOR THE MEASUREMENT OF BEAM INDUCED HIGHER ORDER MODES (HOM) IMPLEMENTED IN THE MicroTCA.4 FORM FACTOR

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## Abstract

Higher order modes (HOM) excited in RF accelerating cavities by a particle beam can be used for electron beam diagnostics. Phase of a monopole HOM provides information about the beam phase relative to the externally induced RF field in a cavity (BPhM) [1]. Furthermore, the amplitude of a dipole mode is proportional to the beam position in the cavity, hence it can be used for beam position monitoring (BPM). In this paper we present a prototype of an instrument implemented in the MicroTCA.4 form factor for the measurement of the HOMs at FLASH and Eu-XFEL. The prototype consists of an analog module, which is used for filtering and conditioning of the selected modes, and a digital module responsible for digitization and signal processing. We present the instruments performance and discuss its influence on the precision of the HOM-based diagnostics.

## INTRODUCTION

HOM couplers dissipate RF energy present in superconducting cavities that is excited by a particle beam. Each cavity at the Eu-XFEL and FLASH has two HOM couplers oriented at 115° with respect to each other [2]. This enables the detection of both orthogonal dipole modes and the measurement of the beam position on the x-y transverse plane.

A train of bunches traversing the cavity at a radial offset  $r$  results in RF power generation at the output of the HOM coupler. The steady-state power is given by [3]

$$P_{out,i} = \frac{q^2 \omega_i^2}{4Q_i} \left(\frac{r}{Q}\right)_i (r \cos \psi_i)^2 f(\omega_i, t_b, \tau_i), \quad (1)$$

where  $q$  is the bunch charge,  $t_b$  is the bunch spacing,  $i$  is a dipole mode characterized by  $\omega_i$ ,  $(r/Q)_i$ ,  $Q_i$ , decay time  $\tau_i = 2Q_i/\omega_i$  and the mode polarization angle  $\psi_i$ . The function  $f$  accounts for the resonant response of the mode:

$$f(\omega_i, t_b, \tau_i) = \frac{1 - e^{-2t_b/\tau}}{2t_b/\tau} \left( \frac{1 - e^{-t_b/\tau}}{1 - 2e^{-t_b/\tau} \cos(\omega_i t_b) + e^{-2t_b/\tau}} \right)^2. \quad (2)$$

For the estimation of the HOM electronics performance, it is necessary to know the peak amplitude of a particular mode, which must be conditioned to fit the full scale of the ADC. In the steady state, voltages associated to each mode are damped sine waves defined by

$$V_i(t) = \sum_k A_k \sin(\omega_i(t + kt_b)) e^{-(t+kt_b)/\tau_i}. \quad (3)$$

Peak amplitude  $A$  can be calculated using the formula:

$$A \approx \sqrt{\frac{P_{out,i} Z t_b}{\tau_i/4 (1 - e^{-2t_b/\tau})}} \quad (4)$$

where  $Z$  is the coupler characteristic impedance. The above formulas are later used to estimate the measurement resolution limit of the designed HOM receiver.

## PRINCIPLES OF THE HOM RECEIVER ELECTRONICS

Figure 1 presents a picture of the HOM electronics (DRTM-HOM1300 carrier and DAMC-DS800) implemented in the MicroTCA.4 form factor. The carrier has a pluggable clock mezzanine and four pluggable filter mezzanines, which are shown in Fig. 2. Figure 3 depicts a simplified block diagram of the HOM receiver with distinguished main noise sources.

Each HOM receiver consists of eight channels, i.e. it can simultaneously measure RF signals from eight HOM couplers connected to the PCB over low phase drift coaxial cables. The cable length can range from about 2 m up to 20 m. RF power dissipated by the HOM couplers is delivered to the filter mezzanines through the carrier. Amplitudes of the measured monopole (1.3 GHz and ~2.45 GHz) and dipole (~1.7 GHz) modes can vary by tens of decibels. Therefore, the modes are split, involving bandpass filters, to three channels having digital attenuators and RF amplifiers for the RF power equalization.

The conditioned RF signals are transmitted over the Zone 3 through an RF coaxial multichannel connector to the digitizer DAMC-DS800, where they are directly sampled by four dual-channel ADCs with the clock frequency of 450 MHz. In the digital domain, due to undersampling, the signals are aliased to the first Nyquist zone. In the next step, all modes are digitally separated, down-mixed and filtered/decimated. Due to the direct RF sampling and digital down-mixing, the HOM receiver can detect various modes without involving a complex and drifty LO generation unit.

The pre-processed data is further sent over a fiber link (QSFP) to a server, where statistical methods, e.g. SVD-method, are applied to extract the amplitude and phase information from the measured HOMs [1].

## HARDWARE DESIGN CHALLENGES

To get the best measurement accuracy, many design stringent requirements have to be met. Transmission of broadband signals over tens of meters requires good

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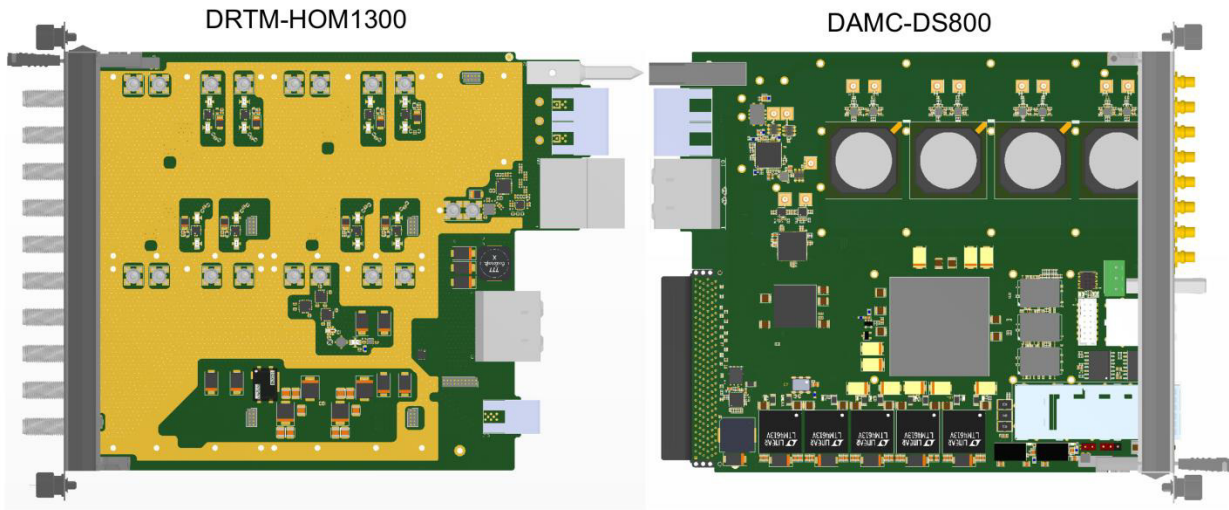


Figure 1: DRTM-HOM1300 carrier is used for distribution, filtering and power conditioning of the detected higher order modes. It is also used for fan-out the clock signal. DAMC-DS800 is a direct RF sampling digitizer. It includes a FPGA for first-stage processing and a QSFP module for fast data transfer.

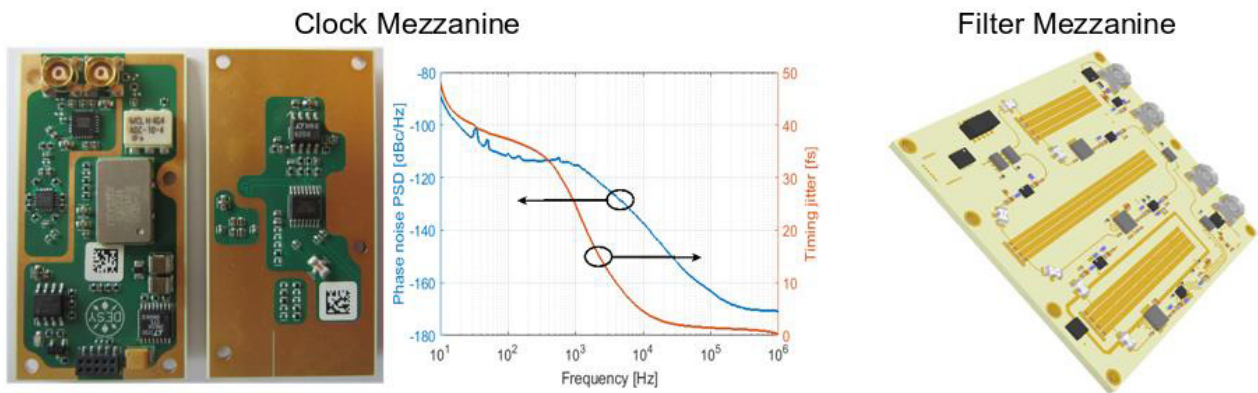


Figure 2: Clock mezzanine includes a VCSO locked to the 1.3 GHz reference signal (phase noise PSD and integrated timing jitter are shown in the plot). Filter mezzanine includes planar bandpass filters, digital attenuators and RF amplifiers for the extraction of required HOMs and their amplitude equalization.

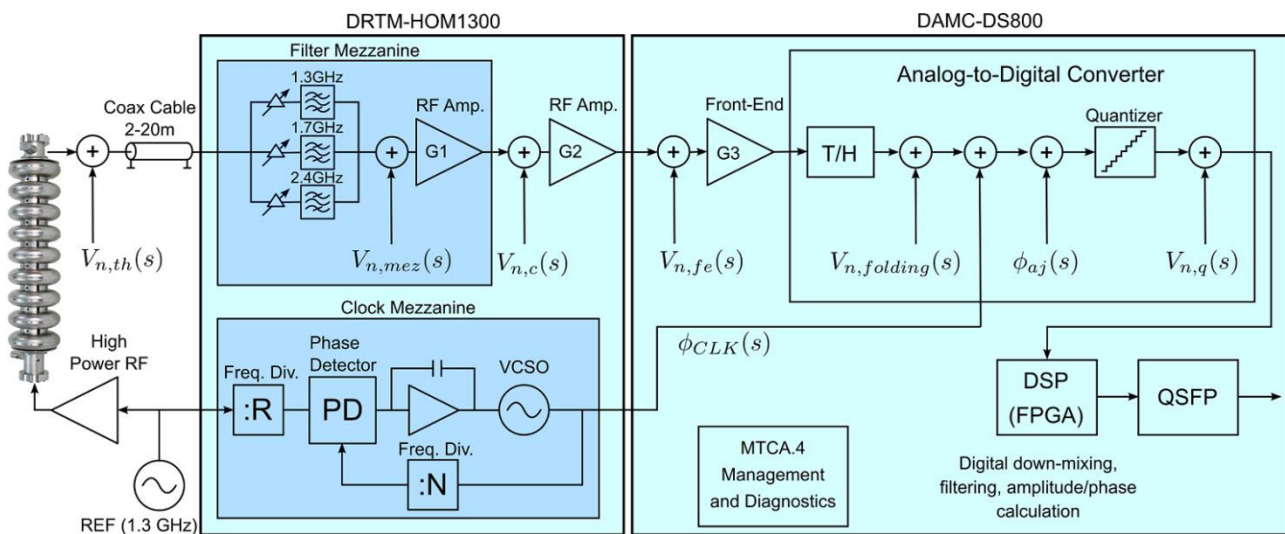


Figure 3: Simplified block diagram of the HOM electronics with distinguished main noise sources for the measurement of the beam induced monopole and dipole modes.

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impedance matching and signal reflections lower than -20 dB. Hence, transitions between RF connectors, striplines and RF components were modelled in the electromagnetic simulator. High density electronics requires special care concerning cross-talks. High isolation (>70 dB) was achieved by vertical splitting of stripline routing in the 10-layer PCB, proper grounding and shielding of particular channels.

One DRTM-HOM1300 module includes 24 bandpass filters. To fit the filters into a limited space and decrease the overall cost, the planar technology was chosen. As far as the BPhM accuracy is directly dependent on relative phase drifts between the monopole modes, the planar filters are designed to have flat group delay and they are encapsulated into temperature controlled aluminium shields.

The ADC clock is a voltage controlled SAW oscillator (VCSSO) locked to the 1.3 GHz reference signal. Noise optimized PLL circuitry enables sampling with ~50 fs rms timing jitter (integrated from 10 Hz to 1 MHz).

As mentioned before, the amplitudes of various modes can highly vary depending on the cavity and beam parameters. Therefore, the HOM receiver must have a high dynamic range covering all possible states, and must include protection elements not to destroy sensitive RF components and ADCs with high peak amplitudes.

## BEAM POSITION MEASUREMENTS

As written before, RF power of a dipole mode can be used for the beam position monitoring (HOM-BPM). Resolution of the position measurement can be estimated by calculating the dipole mode time waveform for particular cavity and beam parameters, and reference it to the residual noise of the HOM receiver.

Table 1: A Selected HOM of D1 Band [4]

Mode	f [GHZ]	$\left(\frac{r}{Q}\right) \left[\frac{\Omega}{cm^2}\right]$	Q
TE111_6	1.7129	5.53	~1e+4

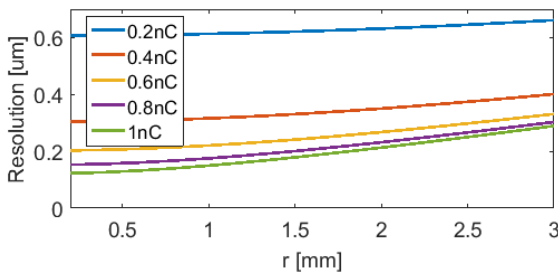


Figure 4: Estimated HOM receiver resolution vs. radial offset  $r$  and vs. beam charge  $q$  for the dipole mode parameters given in Table 1. Calculations are done for the single bunch operation with the macro pulse rep. rate of 10 Hz and measurement resolution of 100 kHz.

The dominating signal-to-noise ratio degradation in the analog part is caused by the RF signal attenuation in long coaxial cables and in all RF components in front of the first amplification stage, which have a noise figure  $NF_1$ . The absolute noise power is further increased because of

the high analog bandwidth of the ADCs (2.7 GHz), which causes the folding of the noise present in the higher Nyquist zones to the first Nyquist zone. Finally, white quantization noise originating in the sampling process is added to the measured waveforms. The estimated BPM resolution (the single bunch operation with the macro pulse rep. rate of 10 Hz) based on the designed receiver for the dipole mode parameters given in Table 1 is shown in Fig. 4. To simplify the calculations, it was assumed that the dipole mode polarization is aligned to the HOM coupler, 1/f noise of RF amplifiers is negligibly small and all noise sources are uncorrelated.

## BEAM PHASE MEASUREMENTS

Phases of the fundamental mode 1.3 GHz and a monopole mode of the second band ~2.45 GHz can be used for the beam arrival time monitoring (HOM-BPhM). Similarly as the BPM resolution, the timing resolution of the HOM receiver can be estimated. However, additional noise sources, i.e. ADC aperture jitter and clock timing jitter, must be considered. Estimations of the BPhM resolution, for the cavity parameters given in Table 2, showed that the dominated noise source is the clock jitter, which equals to ~50 fs rms. Clock signal noise and monopole mode noise are assumed to be uncorrelated. However, some correlation at low frequencies might exist, which would improve the receiver accuracy.

Table 2: A Selected HOM of M2 Band [4]

Mode	f [GHZ]	$\left(\frac{r}{Q}\right) [\Omega]$	Q
TM011_8	2.4499	77.65	~1e+5

## CONCLUSIONS

The eight-channel HOM receiver, based on the MicroTCA.4 standard, was designed. Particular submodules were characterized and simulated in the electromagnetic simulator to get high position and timing measurement resolution. The estimated accuracy of the HOM-BPM is <1 µm and the accuracy of the HOM-BPhM is ~50 fs rms. Next step is the evaluation of the produced modules and comparison of the measurement results with the theoretical models.

## REFERENCES

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