HOM CHARACTERIZATION FOR BEAM DIAGNOSTICS AT THE EUROPEAN XFEL INJECTOR*

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Abstract

Higher Order Modes (HOM) excited by bunched electron beams in accelerating cavities carry information about the beam position and phase. This principle is used at the FLASH facility, at DESY, for beam position monitoring in 1.3 and 3.9 GHz cavities. Dipole modes, which depend on the beam offset, are used. Similar monitors are now under design for the European XFEL. In addition to beam position, the beam phase with respect to the accelerating RF will be monitored using monopole modes from the first higher order monopole band. The HOM signals are available from two couplers installed on each cavity. Their monitoring will allow the on-line tracking of the phase stability over time, and we anticipate that it will improve the stability of the facility. As part of the monitor designing, the HOM spectra in the cavities of the 1.3 and 3.9 GHz cryo-modules installed in the European XFEL injector have been measured. This paper will present their dependence on the beam position. The variation in the modal distribution from cavity to cavity will be discussed. Based on the results, initial phase measurements based on a fast oscilloscope have been made.

INTRODUCTION

Higher Order Modes (HOM) [1] are excited by electron bunches passing the superconducting accelerating cavities of the European X-ray Free Electron Laser (E-XFEL) in the north of Germany [2]. While HOMs can harm the beam, they can also be used for beam monitoring, since their properties depend on the beam properties, such as offset, charge and arrival time.

It is planned to build specialised monitors for the E-XFEL, on one hand for beam alignment and transverse position monitoring [3], and, on the other, for direct, on-line tracking of the beam phase with respect to the accelerating RF [3,4]. These monitors are currently under design [5,6], based on the experience at the Free Electron Laser in Hamburg (FLASH) [7]. There, monitors are installed at so-called TESLA accelerating cavities [3], as well as at 3rd harmonic cavities [8,9], working at 1.3 and respectively 3.9 GHz. The advantages of such monitoring are information on the beam at locations where there is no standard diagnostics, the relatively low cost, the possibility to align the beam in the cavities and reduce harmful HOMs. Also one can obtain information on the cavity alignment inside the cryo-module. The phase measurement will be the first direct, on-line measurement in superconducting cavities.

In the *European XFEL*, energetic electron pulses will produce extremely intense X-ray flashes in the undulator sections. The electrons are accelerated by ca. 100 superconducting cryo-modules, each containing eight cavities. Some of the main parameters of the electron beam are shown in Table 1.

Table 1: Main Parameters of the E-XFEL Electron Beam

Electron beam parameter	
Max. energy [GeV]	17.5
Bunch charge [nC]	0.02 - 1
Max. bunch frequency [MHz]	4.5
Max. bunch number / pulse	2700
Pulse repetition frequency [Hz]	10
Max. pulse length [μm]	600

While the commissioning of the complete accelerator is planned to start by the end of 2016, the first E-XFEL injector started operation in December 2015 [10]. This contains a 1.3 GHz and a 3.9 GHz cryo-module [11]. The latter shapes the bunch energy profile in order to increase the peak current.

A picture of a *TESLA and* a *3rd harmonic cavity* is shown in Fig. 1. The 1.3 GHz TESLA Nb cavity has 9 cells and is ca. 1 m long. RF power is input through the power coupler, while the HOM power generated by the beam is extracted through 2 special couplers mounted in the beam pipes at either end. The 3.9 GHz cavity is basically scaled down by a factor 3 from the TESLA cavity, except mainly the beam pipes which are larger. These enable the propagation of the HOMs through the entire eight-cavity module so that the HOM power is extracted more efficiently. Eight cavities are mounted in either type of module with the power coupler downstream. In this paper we name the cavities by their position within the module, e.g. C4 is the 4th cavity. H1 will denote the HOM coupler close to the input coupler (downstream for 1.3 GHz modules), and H2 at the other cavity end.

The *HOM-based beam position monitoring* idea relies on the fact that the dipole mode strength depends linearly on the beam position and charge. In the TESLA cavities, a dipole mode at ca. 1.7 GHz, with a high R/Q, giving the

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HOM-beam interaction strength [12], was chosen. No clearly identifiable, well separated mode is present in the 3.9 GHz cavities therefore a band of modes around 5.46 GHz was chosen [9]. This band contains modes propagating within the whole cryo-module, therefore in order to get also cavity-related information, modes in the 5th dipole band, around 9.06 GHz will also be monitored, since they are trapped within each cavity.

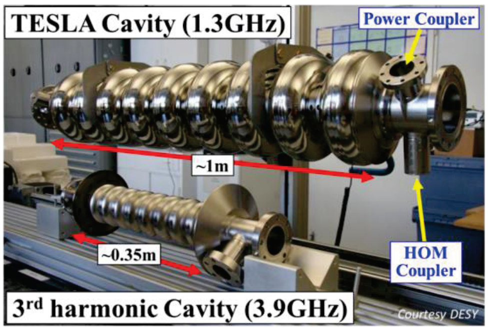

Figure 1: Picture of a TESLA and a 3rd harmonic cavity.

Monopole modes do not depend on the beam offset making a better candidate for beam phase monitoring with respect to the accelerating RF. Modes around 2.4 GHz were chosen for this purpose. No phase diagnostics is planned so far in the harmonic cavities.

In preparation of the HOM-based diagnostics, several measurements and studies were made on both types of cavities for the E XFEL, as summarized in this paper. The following section presents the HOM spectra measured in individual 1.3 GHz cavities during cold RF tests, as well as in individual 3.9 GHz cavities and chains of cavities. In the 3rd section, the beam spectra measured in the TESLA module in the E-XFEL injector are discussed. The subsequent section shows the first beam phase measurements made in the same cavities.

HOM SPECTRA

After production, each superconducting cavity for the E-XFEL went through a series of tests, including transmission measurements between the two HOM couplers during cold tests [13]. Since HOM monitors are planned to be installed at the cavities of the first five 1.3 GHz accelerating modules, their spectra were analysed and are presented in the following subsection. Extensive measurements were made also in the 3.9 GHz cryo-module and are presented later in this section.

Transmission Spectra of 1.3 GHz Cavities

Figure 2 shows the quality factors Q of the modes in the first 3 HOM bands of the cavities in the first five E-XFEL cryo-modules. The data was taken from the cavity database [14]. The modes with high R/Q [12] around 1.7, 1.87 and 2.45 GHz have Qs below 10^5, as required by the multi-bunch beam dynamics.

The frequency spread can be seen in detail for the dipole mode around 1.7 GHz in Fig. 3, together with the neighbouring modes. For several cavities, most in the first cryo-module, the mode is shifted towards higher frequency. These are all from one of the two producing companies, and are not expected to be a challenge for the linac operation. Also for the HOM-based position monitoring the frequency shift does not pose a problem, since the modes are still within the bandwidth of the electronics of 20 MHz, marked by the 2 red lines. The frequency is up-shifted in these cavities also for the modes around 2.4 GHz, also without a problem for the electronics [6].

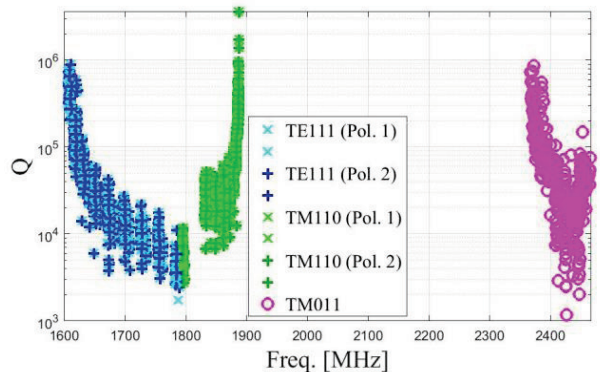

Figure 2: Quality factors of the first 2 dipole bands (TE111 and TM110-like) and of the first monopole HOM band (TM011-like) versus mode frequency. Each dipole mode has 2 polarizations.

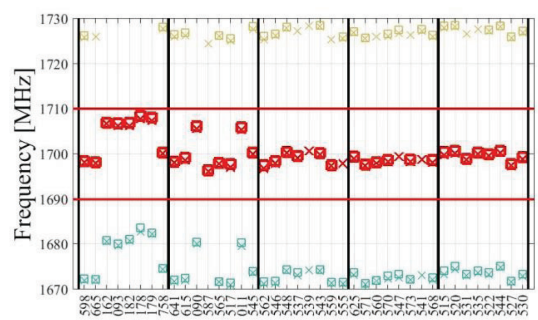

Figure 3: Frequency of the 1.7 GHz dipole mode (red marks), to be used for beam position monitoring, for the cavities in the first 5 TESLA modules. The neighbouring modes are also plotted. The black vertical lines, delimit each cryo-module. The red lines mark the bandwidth of the electronics.

Transmission Spectra of 3.9 GHz Cavities

The spectra of the individual 3.9 GHz cavities were measured before assembly at room temperature [15,16]. A very similar spectrum was found for the 1st and 2nd dipole bands. The 5th dipole band, on the other hand, is very sensitive to slight geometrical variations, which is reflected by the very different spectra observed for the different cavities.

After assembly and cool down, the spectra were measured again for each cavity in the module as well as for the whole chain of 8 cavities. Fig. 4 show the transmission spectra S21 of the first 2 dipole bands measured across C1, across the first 4 cavities (C1-C4), and through the entire chain (C1-C8). One observes that most of the modes

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propagate through the entire chain. The qualitative behaviour expected from simulations was confirmed by the measurements [17].

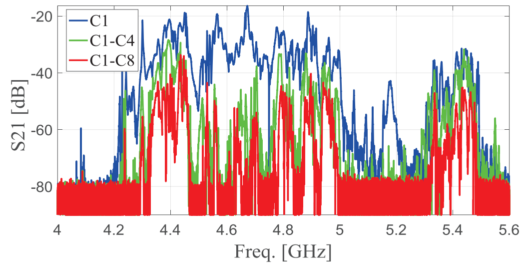
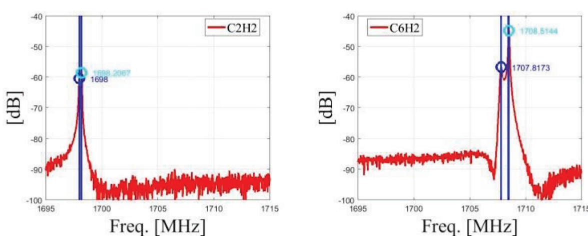


Figure 4: S21 measured across the first cavity, across the first 4 cavities and across the whole cavity chain of the 3.9 GHz module in the E-XFEL injector.

BEAM SPECTRA IN 1.3 GHZ CAVITIES

During the commissioning of the E-XFEL injector, we measured the spectra around the frequencies of interest for all eight cavities of the 1.3 GHz module. Fig. 5 shows the spectrum around 1.7 GHz measured from C2H2 and C6H2 with a Tektronix Real-Time Spectrum Analyser (RSA6114A). One notices the double peaks, indicating the two polarisations of each dipole mode. The mode frequency is quite different for the two cavities, and one notices the different separation of the peaks for the two cavities.



a b

Figure 5: Beam spectrum of dipole mode to be used for beam position monitoring, for C2H2 (a) and C6H2 (b). Each curve is the average of 5 spectra. The blue vertical lines are the mode frequencies from [14].

In order to study the mode behaviour, the transverse beam position was varied with two magnetic steerers, one horizontal and one vertical. Two beam position monitors (BPM) [18], one upstream and one downstream of the module were used to inferr the beam position in the middle of each cavity. The RF as well as all magnets between the two BPMs were switched off.

The dependence on the beam position of the amplitude of each of the two polarisations for C6H2 is shown in Fig. 6. The left plot corresponds to the left peak in Fig. 5b, while the right plot is for the 2nd polarization. One notices that the lower polarization responds mostly to vertical beam movement, and vice versa. There is however a slight rotation of the two polarisations. This rotation differs from cavity to cavity. For us this means that we cannot use for diagnostics one single mode, like in a standard cavity beam position monitor, but we have to employ a complex data analysis procedure [3,9].

From the analysis of such transverse scans one can deduce the relative transverse cavity alignment inside of the cryo-module [3]. This requires, especially at such low energies, 4D scans filling the transverse space (x,x′,y,y′). Such scans are planned after the prototype electronics is available for beam tests. Note that for a more accurate analysis of the two polarizations a Lorentzian fit has to be made.

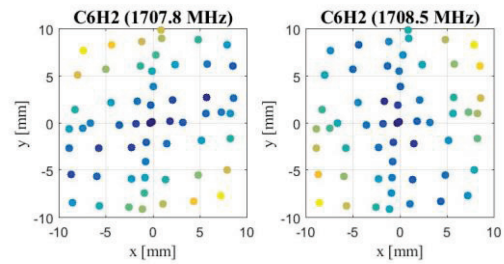


Figure 6: HOM signal amplitude from C6H2 as a function of the beam position in the middle of C6. The two plots correspond to the two polarizations in Fig. 5b.

Figure 7 shows the beam spectrum from C6H2 around 2.4 GHz. The vertical lines indicate where HOMs peaks are expected [14]. Several peaks can be seen in addition. None of the peaks vary with the beam position. It was found that the additional peaks come from the nearby cavities, i.e. their monopole modes propagate through the beam pipe to the HOM coupler of the neighbouring cavity. This is not expected to be an issue for the HOM-based phase monitoring.

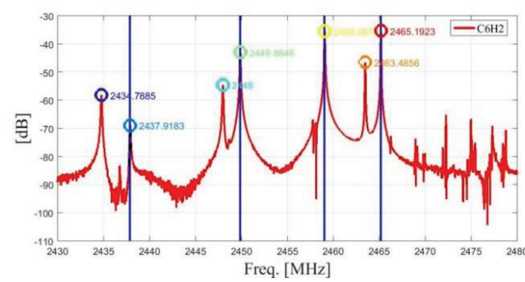


Figure 7: Monopole mode spectrum of C6H2. The blue vertical lines are the mode frequencies from [14].

HOM-BASED PHASE MEASUREMENTS

Although the HOM couplers have been designed to reject the accelerating mode, there is still a significant amount of RF power leaking through. This enables us to measure at the same time, through the same cable, both beam excited modes around 2.4 GHz, and the accelerating mode at 1.3 GHz, and determine the RF phase with respect to the beam arrival time [3].

Such measurements were made at the E-XFEL by splitting the signal from one coupler, filtering around 1.3 and around 2.4 GHz respectively, then recombining the two signals and monitoring the signal with a Tektronix scope TDS6604B with 20GS/s and 6 GHz bandwidth. Similar measurements have been made at FLASH [4]. Fig. 8 shows the phase obtained from both HOM couplers of one cavity. Initially the phase was calibrated to show

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0 deg (the first 25 measurements). Then the RF phase was changed by 5 degrees in each direction. The setup could monitor this change. By comparing the measurement from each coupler, a phase resolution of 0.12 deg rms is obtained in this case.

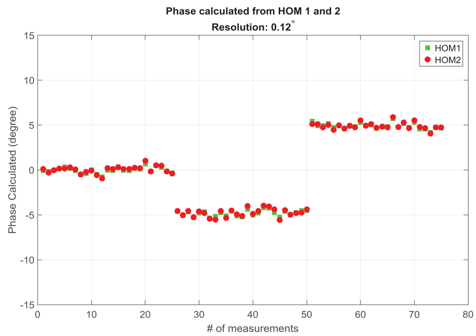

Figure 8: RF phase with respect to the beam calculated from signals from both HOM couplers, HOM1 (green) and HOM2 (red), of one cavity.

SUMMARY

In preparation for the HOM-based diagnostics now under design for the E-XFEL, we analysed the HOM spectra in the first five 1.3 GHz modules and the 3.9 GHz module. The selected modes are within the bandwidth of the electronics. For the monopole modes one could also observe peaks from the neighbouring cavities, which do not constitute a problem for the phase monitoring.

The dependence of the dipole spectra on the beam position was analysed. There is a variation from cavity to cavity in the polarization rotation, which makes a complex signal processing necessary.

Further measurements are planned after the start of beam operation of the entire E-XFEL linac, and when the prototype electronics is available for beam tests.

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