ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-TUPRB075



# HIGHER ORDER MODE SPECTRA STUDY OF 3.9 GHz SUPERCONDUCTING RADIO FREQUENCY CAVITIES FOR THE EUROPEAN XFEL*

L. Shi[1,†], N. Baboi, P. Pierini[‡], E. Vogel, A. Sulimov, T. Wamsat
Deutsches Elektronen-Synchrotron DESY, 22607 Hamburg, Germany
N. Joshi[1], R. M. Jones[1], The University of Manchester, Manchester, M13 9PL, UK
S. Reiche, Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland
[1] also at The Cockcroft Institute of Accelerator Science and Technology, Daresbury, WA4 4AD, UK

*Abstract*

It is important to verify both by simulation and experiments the wakefields in superconducting radio frequency (SRF) cavities, which can degrade the electron beam quality considerably or impose excessive heat load if left undamped. In this paper, we investigate the Higher Order Mode (HOM) spectra of the 3.9 GHz SRF cavities, which are assembled in a cryogenic module and are used to linearize the longitudinal phase space of the electron beam in the injector of the European XFEL. The HOM spectra are significantly different from the ones from a single cavity due to the coupling of the modes amongst cavities. The measurements not only provide direct input for the beam dynamics studies but also for the beam instrumentation utilizing these modes. The mode spectra are also investigated with a number of numerical simulations and the comparison with measurements shows favorable agreement.

## INTRODUCTION

The E-XFEL (European X-ray Free Electron Laser) is a free electron laser facility based on the superconducting accelerating technology, which enables the generation of 27000 X-rays pulses per second for various experiments [1]. The facility is approximately 3.4 km long and contains 97 accelerating superconducting cryomodules. Each module hosts eight superconducting TESLA (TeV Energy Superconducting Linear Accelerator) [2] cavities that operate at approximate 20 MV/m to accelerate the electron beam up to 17.5 GeV for the X-ray production. In order to reach a kA beam current for the later X-ray production in the undulator line, three magnetic bunch compressors are used [1].

At the injector part of the E-XFEL, there is a cryomodule hosting eight 3.9 GHz cavities which are used to linearize the longitudinal beam phase space for better bunch compression [3]. The module is shown in Fig. 1 and technical details can be found in [3, 4].

When an electron beam traverses a superconducting accelerating cavity, it excites electromagnetic fields, which can be decomposed into a series of modes, resonant electromagnetic fields that oscillate with distinctive frequencies and field distributions. Among them, HOMs (Higher Order Modes) are the modes with frequencies higher than the accelerating mode. These modes are in general detrimental to the electron beam quality and can greatly influence the beam dynamics and cause excessive heat load for the cryogenics if left unchecked [1, 5]. Therefore, they have to be damped via specially designed RF couplers [2, 6].

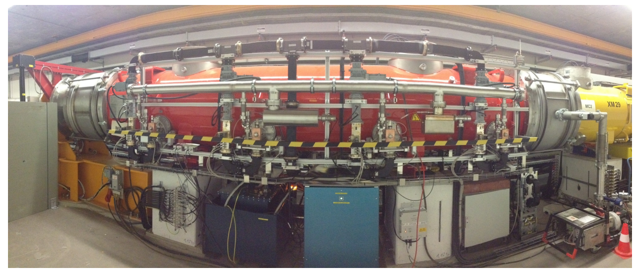

Figure 1: The third harmonic module with eight cavities inside at the injector of the E-XFEL.

On the other hand, these modes can be used for the beam instrumentation such as beam position monitoring [7, 8], beam phase monitoring [9], cavity tilt inference [10] developed for the TESLA 1.3 GHz cavities. The beam position monitors have also been developed for the four 3.9 GHz cavities for FLASH (Free Electron Laser in Hamburg) [11].

These 3.9 GHz cavities are a down scaled version of the 1.3 GHz cavities. The wakefield effect is more severe and complicated than for the 1.3 GHz cavities [11]. Therefore extensive measurements were made to ensure that all modes in the first few dipole bands are damped sufficiently. On the other hand, this guarantees that the signal level is sufficient to drive a beam monitor.

Numerical simulation is required in order to understand the electromagnetic mode behavior, which also provides reference for the experimental measurements. The direct simulation of eight cavities would require significant simulation memory and computation power. Therefore two techniques that try to reduce the computation efforts are developed. The method based on the so-called State Space Concatenation (SSC) is reported in [12]. The results based on the Generalized Scattering Matrix (GSM) are reported here. These methods significantly reduce the computation memory and time and make the simulation feasible on a desktop class computer.

* Work supported by EuCARD[2]
† Now at Paul Scherrer Institut; liangliang.shi@psi.ch
‡ Now at European Spallation Source, ESS, 225 92 Lund, Sweden

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-TUPRB075

We first present the simulation of 3.9 GHz cavities based on GSM method. It is then followed with the experimental measurements. A conclusion and outlook section ends the paper.

## SIMULATION OF THE 3.9 GHz CAVITY CHAIN

For the 3.9 GHz cavities, the HOM frequencies are mostly above the cut-off frequency of the connecting beam pipe and therefore most of them are able to travel to the nearby cavities. This necessitates the simulation of all eight cavities as a chain. However, a direct simulation would require a significant amount of computational power and memory. Two sets of numerical codes have been developed and employed in the time domain (SSC [12]) and frequency domain (GSM [13]) in order to study the eight coupled cavities. Both codes have achieved reasonable agreements with experiments. The GSM method is employed here. The fundamental idea behind this code is to decompose a large structure into several basic blocks. The transmission properties can be simulated individually and accurately for each block. By combining all the unit studies, we can retrieve the electrical properties of the large structure. A 3.9 GHz cavity is decomposed into one end-cup with fundamental coupler (FP) and HOM coupler 1 (HOM1), eight mid-cups, and one end-cup with HOM coupler 2 (HOM2). These basic components are shown in Fig. 2. The details of the simulation can be found in reference [13].

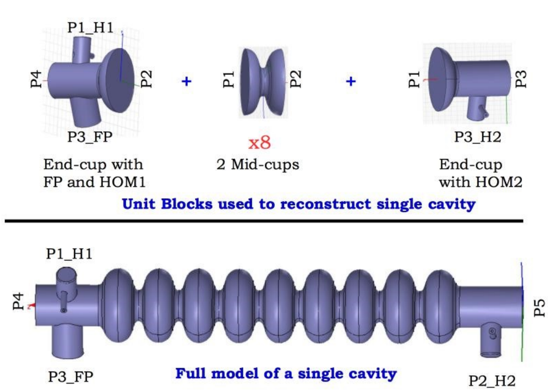


Figure 2: Computational blocks for GSM [13].

A transmission spectrum was obtained by cascading the results for each component defined in Fig. 2. The spectrum is compared with a simulation for a cavity without decomposition as in Fig. 3. Both spectra resemble each other very well.

The chain of eight coupled cavities (see Fig. 4) is then simulated in a similar way [13]. Based on the transmission spectrum, the external quality factor for all the modes are calculated and found to be below $10^4$, which indicates sufficient damping.

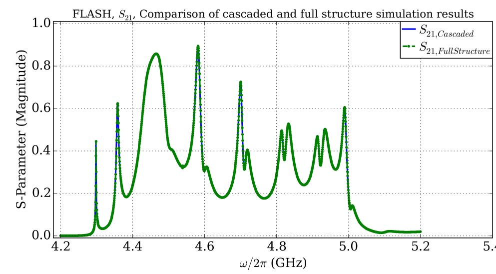


Figure 3: Comparison of transmission spectrum ($S_{21}$) of a single cavity based on GSM ($S_{21}$, cascaded) and direct simulation ($S_{21}$, FullStructure) [13]. The frequency is defined as $\omega/2\pi$.

## EXPERIMENTAL MEASUREMENTS OF THE 3.9 GHz CAVITIES

The cavity chain is schematically shown in Fig. 4. The cavities installed in the module are named: 3HZ010, 3HZ005, 3HZ012, 3HZ013, 3HZ008, 3HZ007, 3HZ004 and 3HZ011. For simplicity only their number is shown in the figure. These cavities underwent several tests after fabrication: measurements of the fundamental 3.9 GHz mode, tuning of the HOM couplers, vertical test [14]. The HOM1 coupler and the power coupler are always upstream with respect to the HOM2 coupler.

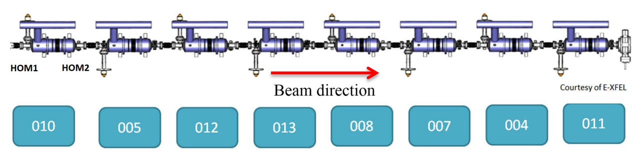


Figure 4: Chain of eight coupled 3.9 GHz cavities.

We have measured the HOM spectra for both single and coupled cavities from HOM1 to HOM2 with a vector network analyzer of type HP8720c at a fine step. The cavities were measured both in the normal and superconducting states. The spectra for 3HZ010 are shown in Fig. 5. When the cavity is cooled from room temperature to 2 K, there is an approximate 10 MHz shift to higher frequencies. The spectra at 2 K were analyzed to extract the mode frequencies (based on Eq. (1)) and the associated quality factors. The resonant peaks in the spectra can be described by Lorentz distributions:

$$y = \sum_i \frac{a_{0i}}{1 + \left(\frac{f - f_{0i}}{\Delta f_i}\right)^2}, \qquad (1)$$

where $i$ is the mode index, $a_{0i}$ the peak amplitude, $f_{0i}$ the central frequency and $\Delta f_i$ the half width at half maximum of the peak. The quality factor can be calculated with $Q_i = \frac{f_{0i}}{2\Delta f_i}$. The results are summarized in Fig. 6. Most of the modes have quality factors below $10^4$, indicating a sufficient damping. The analysis has been done for all the cavities and they show quite similar damping. The comprehensive results and the comparison with simulations will be reported in a later publication.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-TUPRB075

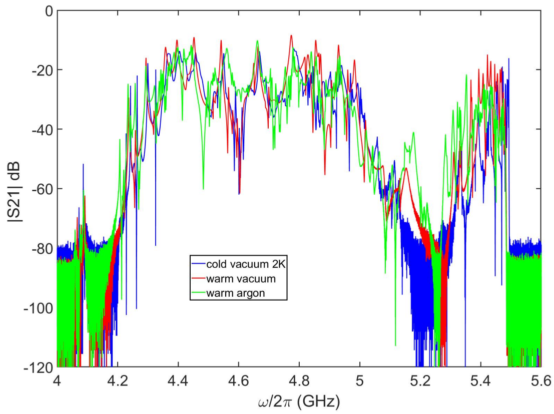


Figure 5: Spectra of 3HZ010 in three experimental states: in superconducting at 2 K; at room temperature with vacuum; at room temperature but filled with argon.

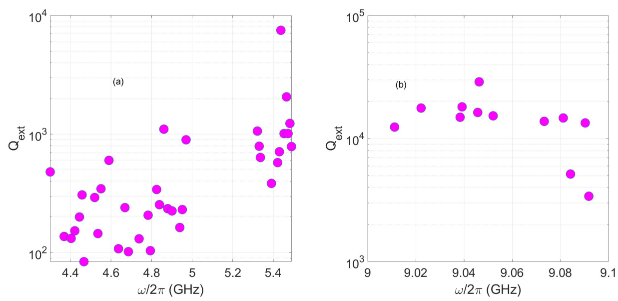


Figure 6: Summary of mode frequencies and external quality factors $Q_{ext}$ for cavity 3HZ010 in superconducting state. (a) First and second dipole band (b) fifth dipole band.

For the transmission spectra of the coupled cavity chain, the measurements were performed from HOM1 to HOM2 along the chain (see Fig. 4). When the transmission was measured for a certain pair of HOM couplers, the rest of the couplers were terminated with 50 Ω loads. The spectra were recorded for the frequency range of 4-5.6 GHz with a step of 5 kHz and for 9-9.1 GHz with a step of 300 Hz.

Figure 7 shows a summary of the HOM spectra. The cavities are tuned and the whole module is in superconducting state (at  2 K). It can be clearly seen that the spectrum gets more and more complicated due to the coupling to succeeding cavities. In principle, each mode in a cavity splits into eight modes if we view the string of cavities as a super-cavity structure. The bandpass structure becomes finer and finer as more cavities are coupled. The transmitted power from the first to the last HOM coupler shows approximately −40 dB attentuation. Besides, the measurements confirmed that, as expected, several modes at 9-9.1 GHz do not propagate. These are planned to be used for local measurement of the beam position in each cavity, while propagating modes in 4-5.6 GHz range can be used for measurements in the whole module.

These measurements together with the experience at FLASH [11] provide the basis for the instrumentation of

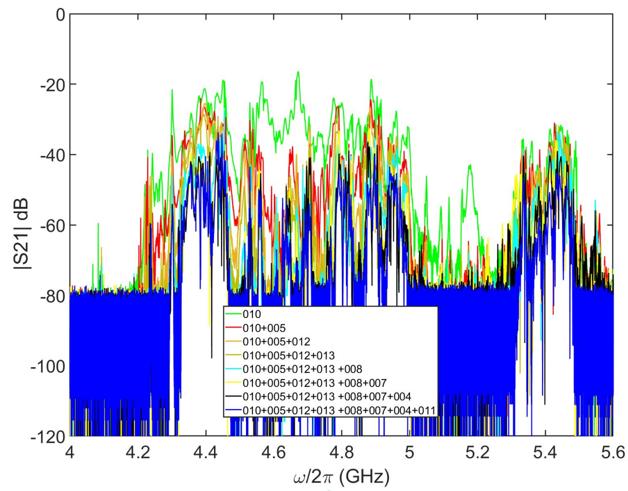


Figure 7: Transmission spectra for the cavity chain in Fig.4: 010 represents cavity 3HZ010; 010+005 for the transmission from cavities 3HZ010 to 3HZ005 etc.

the HOMs as beam position monitor or for beam steering along the module. However, dedicated beam time would be helpful to finely tune the slice of spectra that couples more strongly to the electron beam and thus provides higher resolution.

## CONCLUSION AND OUTLOOK

We presented HOM spectra studies for eight coupled 3.9 GHz cavities through experimental measurements and numerical simulation. The simulated spectra captured the coupling mechanism and faithfully represent the transmission spectra of eight cavities with some discrepancies. These come from many factors. The major ones are potentially: We replaced the connecting bellows with waveguides in the simulation in order to reduce the computational load; the frequency step was 500 kHz for simulations but 5 kHz for the experiments; the actual cavity shape is not precisely known due to the production imperfections and preprocessing after the cavity fabrication aforementioned. All modes are sufficiently damped.

In general, the frequency range of 4.2-5.6 GHz can be used for beam position prediction in the whole module and the range of 9-9.1 GHz can be used for beam position prediction for each cavity. The associated electronics target these two frequency ranges.

## ACKNOWLEDGEMENTS

The authors would like to thank all the colleagues supporting the measurements at AMTF and at the European XFEL.

The work is part of EuCARD-2, partly funded by the European Commission, GA 31245. The writing of this paper is during the funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 701647.

## REFERENCES

[1] M. Altarelli *et al.*, Eds., *XFEL: The European X-Ray Free-Electron Laser. Technical Design Report*. 2006, ISBN: 9783935702171. DOI: 10.3204/DESY_06-097.

[2] B. Aune *et al.*, "Superconducting TESLA cavities," *Phys. Rev. ST Accel. Beams*, vol. 3, p. 092 001, 9 Sep. 2000. DOI: 10.1103/PhysRevSTAB.3.092001.

[3] C. G. Maiano *et al.*, "Validation of the superconducting 3.9 GHz cavity package for the European X-ray Free Electron Laser," *Phys. Rev. Accel. Beams*, vol. 20, p. 042 005, 4 Apr. 2017. DOI: 10.1103/PhysRevAccelBeams.20.042005.

[4] E. Vogel *et al.*, "Considerations on the third harmonic RF of the European XFEL," in *Proceedings of the 13th International Workshop on RF Superconductivity, Beijing*, 2007, pp. 481–485.

[5] R. M. Jones, "Wakefield suppression in high gradient linacs for lepton linear colliders," *Phys. Rev. ST Accel. Beams*, vol. 12, p. 104 801, 10 Oct. 2009. DOI: 10.1103/PhysRevSTAB.12.104801.

[6] T. Khabiboulline, I. Gonin, and N. Solyak, "New HOM coupler design for 3.9 GHz superconducting cavities at FNAL," in *2007 IEEE Particle Accelerator Conference (PAC'07)*, Jun. 2007, pp. 2259–2261. DOI: 10.1109/PAC.2007.4441216.

[7] S. Molloy *et al.*, "High precision superconducting cavity diagnostics with higher order mode measurements," *Phys. Rev. ST Accel. Beams*, vol. 9, p. 112 802, 11 Nov. 2006. DOI: 10.1103/PhysRevSTAB.9.112802.

[8] L. Shi, N. Baboi, and R. M. Jones, "Stability and resolution studies of HOMBPMs for the 1.3 GHz superconducting accelerating cavities at FLASH," *Physics Procedia*, vol. 77, pp. 42–49, 2015, International Conference on Laser Applications at Accelerators, LA3NET 2015, 25-27 March 2015, Mallorca, Spain, ISSN: 1875-3892. DOI: 10.1016/j.phpro.2015.11.008.

[9] L. Shi, N. Baboi, and R. M. Jones, "Beam phase retrieval based on higher order modes in cylindrical superconducting radio frequency cavities," *Review of Scientific Instruments*, vol. 89, no. 10, p. 105 105, 2018. DOI: 10.1063/1.5040191.

[10] T. Hellert, N. Baboi, and L. Shi, "Higher-order mode-based cavity misalignment measurements at the free-electron laser FLASH," *Phys. Rev. Accel. Beams*, vol. 20, p. 123 501, 12 Dec. 2017. DOI: 10.1103/PhysRevAccelBeams.20.123501.

[11] P. Zhang, *Beam Diagnostics in Superconducting Accelerating Cavities: The Extraction of Transverse Beam Position from Beam-Excited Higher Order Modes*. Springer Science & Business Media, 2013.

[12] T. Flisgen *et al.*, "Eigenmode compendium of the third harmonic module of the European X-ray Free Electron Laser," *Phys. Rev. Accel. Beams*, vol. 20, p. 042 002, 4 Apr. 2017. DOI: 10.1103/PhysRevAccelBeams.20.042002.

[13] N. Joshi, N. Baboi, R. M. Jones, and L. Shi, "Simulation of electromagnetic scattering through the E-XFEL third harmonic cavity module," in *Proceedings, 7th International Particle Accelerator Conference (IPAC 2016): Busan, Korea, May 8-13, 2016*, 2016, pp. 3001–3004. DOI: 10.18429/JACoW-IPAC2016-WEPOY007.

[14] D. Reschke, "Performance of superconducting cavities for the European XFEL," in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, (Busan, Korea), May 2016, pp. 3186–3191. DOI: 10.18429/JACoW-IPAC2016-THYB0.