VIBRATION STABILITY STUDIES OF A TYPE III+ XFEL/FLASH SUPERCONDUCTING ACCELERATING MODULE OPERATING AT 2 K

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Abstract

In this work, we present a collection of data from the tests of mechanical dynamic stability performed on a latest generation (Type-III+) FLASH (Free electron LASer in Hamburg) superconducting accelerating module (cryomodule). Mechanical transfer functions (TF) from the vacuum vessel to the magnet package and magnet vibration levels during cryogenic/RF tests on the CryoModule Test Bench (CMTB) have been measured using inertial velocity sensors (geophones). A preliminary experiment for a further validation of the results by optical methods has also been attempted. In addition, vibration stability in relation with positioning the quadrupole at the center of the cold mass has been investigated.

INTRODUCTION

Design of the third generation (Type-III) FLASH cryomodules is the baseline design for the linac of the European X-Ray Free Electron Laser (XFEL) [1] and of the International Linear Collider (ILC) [2]. FLASH Type-III cryomodules [3] are equipped with a string of eight 9-cell niobium superconducting cavities and a beam position monitor (BPM)/magnet package, located at the end of the module, containing three independent superconducting magnets: a super-ferric quadrupole, a vertical and a horizontal dipole. The cavities, operating at 2 K, and the magnet package, operating at 4.5 K, are suspended from a 300-mm diameter Helium Gas-Return-Pipe (HeGRP), acting as a support structure together with three thermally insulating adjustable posts on top of the vacuum vessel. The support structure also holds the two aluminum thermal shields at 4.5 K and 40/80 K.

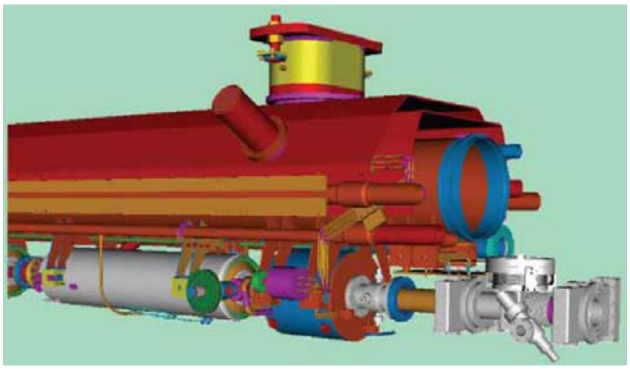

Figure 1: 3-D model cut-away view of the Type-III+ cryomodule cold mass end group: from the left, the last cavity of the string, the magnet/BPM package, the HOM absorber and the beam pipe valve.

Longitudinal positioning of the cavities is made independent from the elongation and contraction of the HeGRP by anchoring them to a reference Invar rod, attached to the center of the HeGRP at the middle post, and using low friction sliding supports.

Vibration level experienced by the superconducting quadrupoles hosted inside the cryomodules is a relevant issue for the engineering design of both the XFEL and the ILC, and it has been extensively investigated in the last few years [4-8]. The motivation is that uncorrelated fast motion of the magnets, generated by ground vibrations and technical systems (vacuum and cryogenics), is a major cause of pulse-to-pulse beam position jitter at the end of the linac [9]; in the ILC case, an excessive beam jitter could also result in emittance growth.

The so-called Type-III+ design, includes modifications, with respect to Type-III, which should be tested on-field before the final design of the XFEL prototype. Besides the changes in the cavity-to-cavity spacing to match the RF wavelength, the introduction of the latest design fast piezo tuners and of the high-order-modes (HOM) absorber in the interconnection between the modules, the main modification is the new support of the magnet package and its operation at 2 K in a superfluid He-II bath. The magnet package is now suspended from the HeGRP by using a bearing system, similar to the bearing system of the cavities that allows axial movement during the cool-down. The axial position with respect to the central post is kept constant by connecting the package to the Invar rod. With the operation at 2 K, the magnet cryostat is not anymore part of the 4.5 K highly pressurized circuit for the inner thermal shield refrigeration, which, as experienced in FLASH, may produce large excess vibrations [8]. In this paper, we present results of the recent investigation, carried out on a Type-III+, named Module 8, during its test run on the CMTB at DESY, in which the benefits of the new cryogenic layout in terms of mechanical stability and the stiffness of the new magnet support have been evaluated experimentally.

EXPERIMENT

Cryomodule Instrumentation

The cold mass of Module 8 has been instrumented, during its assembly, with three seismic sensors. Two single axis geophones, one vertical GS-11D from Oyo Geospace [10] and one horizontal (oriented in direction transverse to the beam pipe) SM6-HB from Sensor b.V [11], have been affixed to the front face of the magnet helium vessel; an additional vertical GS-11D has been installed at the center of the cold mass on the bracket supporting cavity number 4. These devices have demonstrated reliable operation down to 2 K temperature with no loss of sensitivity, and remote calibration capability. The experimental setup at the CMTB was completed by additional vertical and horizontal SM6 placed on top of the vacuum vessel as room temperature reference channels. A further vertical SM6 on the ground was used to provide amplitude and spectral information on the seismic activity of the site during each measurement. The response of all the geophones has been extended from the natural 4.5 Hz down to ~ 0.7 Hz with non-linear inverse filtering; an equivalent displacement noise level around $1\,\text{nm}/\sqrt{\text{Hz}}$ at 1 Hz has been achieved after digitization with a 16-bit USB ADC (Agilent U2300), both at room temperature and at 2 K. Data processing is described in detail in [6] and references therein. The three sensors on the cold mass will also be used to monitor vibrations of the module during its transportation test (Hamburg-Saclay-Hamburg) scheduled by fall this year. For this application, the mechanical dynamic range of the geophones will be extended to a few g by means of a specifically designed over-damping amplifier [12].

Mechanical Transfer Function Measurements

Dynamic mechanical stability of the updated magnet support design was investigated by measuring the transfer function between the vacuum vessel and the quadrupole. The DESY site ground motion, with root-mean-square (rms) amplitudes, often exceeding 100 nm in the frequency band 1-100 Hz [13], has been used as broadband excitation source of vibration.

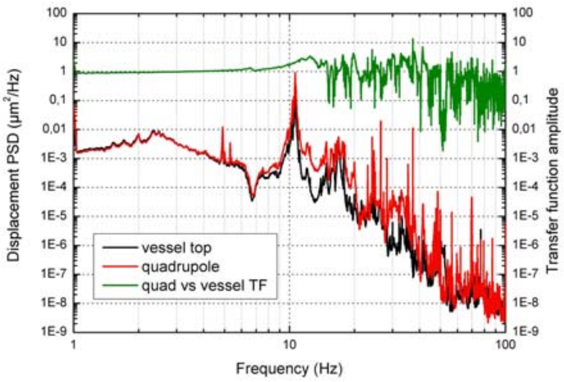

Figure 2: Quadrupole vs. vessel top horizontal PSDs and TF.

This measurement has been done on the CMTB, at room temperature, at the end of the operational test of the cryomodule while both of the isolation vacuum pumps were switched off. In the horizontal transverse direction, the displacement power spectral densities (PSD) are characterized (Fig.2) by two large amplitude peaks at 10.5 Hz and 15 Hz, corresponding to rigid body modes of the vacuum vessel on its support system, and at higher frequencies by a number of lines produced by technical noise sources.

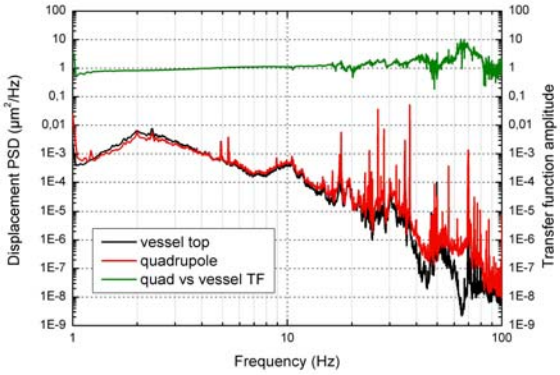

Figure 3: Quadrupole vs. vessel top vertical PSDs and TF.

The calculated TFs do not show any evidence for mechanical resonances of the quadrupole support structure up to ~50 Hz in the horizontal transverse (Fig. 2) and up to ~ 80 Hz in the vertical (Fig. 3) directions.

Validation by Optical Methods

Module 8 is provided with two optical lines of sight from two viewports on the main vacuum vessel towards the magnet. Suitable cuts through the thermal shields allow a laser beam to hit diffusive retroreflecting targets to measure the relative motion between the magnet and the vacuum vessel along vertical and horizontal transverse directions by interferometric methods.

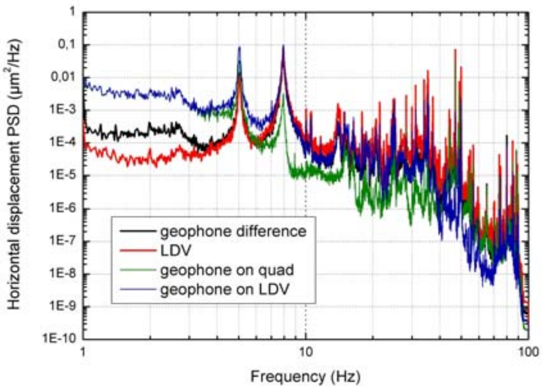

Figure 4: Comparison between the quadrupole vs. vacuum vessel relative motion measured with geophones and the LDV.

This measurement was proposed to cross check and further validate the results obtained with the inertial sensors. A room temperature, preliminary test was carried out, after the completion of the module assembly, by using a commercial laser Doppler velocimeter (LDV) OFV-505 from Polytec GmbH [14]. The instrument, a digitally demodulated Mach-Zender heterodyne interferometer, provides an output proportional to the relative velocity between the laser head and the target. In this experiment, the LDV signal was compared with the relative velocity calculated using the geophone on the quadrupole and a reference geophone placed on the laser head support. Results, for example, for the horizontal direction (see Fig. 4 and Fig. 5) show a substantial agreement between the LDV and the two geophone signal difference confirming the quality of the measurements done with the seismic sensors. Nevertheless, the relative motion amplitude, obtained by numerical integration of the LDV output, is certainly overestimated because of the influence of the rocking modes of the cryomodule as supported in the experimental hall where the test was performed. Both modes (the two peaks at 5 Hz and 8 Hz in the PSDs) have much larger amplitudes at the LDV head position producing significant differential linear velocities between head and target. This limitation can only overcome by a pure distance measurement for which new tests have been planned.

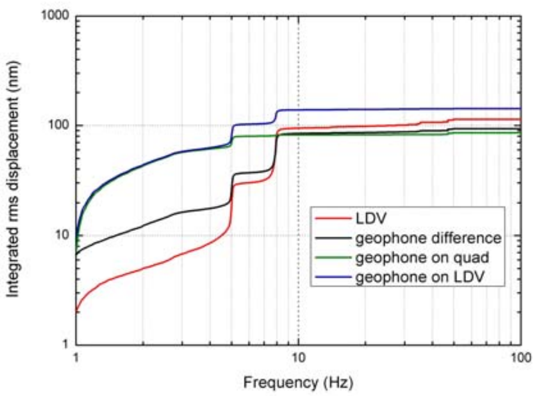

Figure 5: Corresponding integrated rms of Fig. 4. Values at frequency f are the rms integrated spectra from 1 Hz to f. The lower signal amplitude at low frequencies from the LDV is due to the imperfect response matching between the two geophones, limiting the common mode motion rejection.

Cryogenic Tests

In these tests, we have investigated the sensitivity of the vibration level measured on the cold mass to the parameters of the 4.5 K shield circuit, which were found to be rather strong in Type-II and Type-III design [8]. The inlet pressure of the inner shield circuit has been regulated to establish two phases or single phase He; different flow rates have also been tested (see Fig. 6). No correlation between the parameter changes (even stopping the flow) and the vibration amplitude has been found, with the signal levels just following the ground motion trend. Higher motion levels have been detected only, but not systematically, during transient phases. Noise spectra (see Fig. 7) were shaped at low frequency (1-20 Hz) by the DESY site ground motion, with the two characteristic traffic induced bumps around 2 and 10 Hz. At higher frequencies, technical noise sources are dominating with strong lines at 24.7, 26.4, 28.3, 35.4, 37.2, 44.7, 49, 69.8, 74.2 Hz. The lines at 24.7, 49.4, 74.2 Hz have been identified as generated by a vacuum pump connected to the bellow between the module and the end cap on the magnet side.

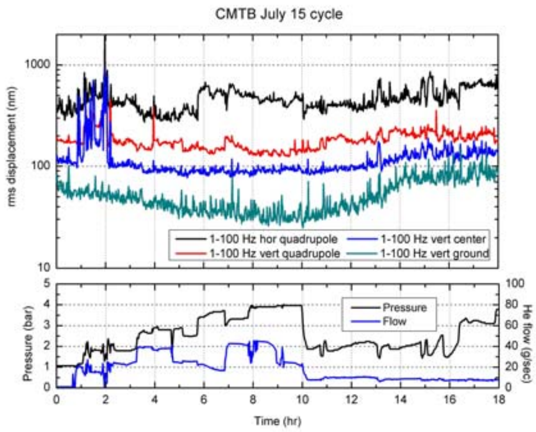

Figure 6: rms displacement integrated from 1 to 100 Hz measured on the cold mass for different settings of 4.5 K circuit, compared with the floor vibrations. In the first hour of the test the circuit was closed.

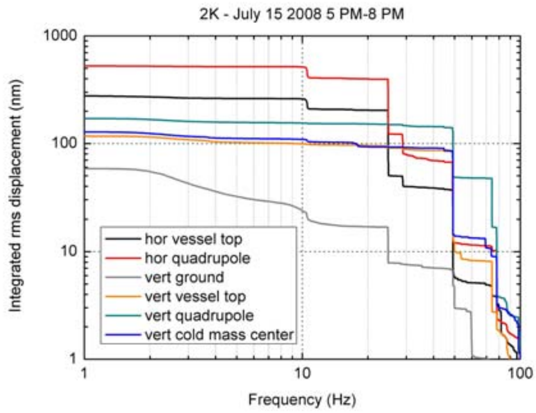

Figure 7: Typical rms amplitude spectra measured on Module 8 during its cold test on the CMTB.

In the horizontal transverse direction, the quadrupole integrated rms motion was ranging from 400 to 600 nm as a function of the excitation level of the 10.5 Hz rocking mode. In the vertical direction, levels lower than 200 nm, with a large contribution coming from the vacuum pumps, have been observed during the two weeks duration of the Module 8 cold test. No level change for all of the sensors with respect to room temperature has been observed.

Comparison of Quadrupole Positioning at the End of the Cold Mass vs. Center

One of the major changes in the ILC cryomodule design (so-called Type-IV) with respect to FLASH/XFEL is the positioning of the magnet package at the center of the cold mass. Besides alignment issues, the other believed advantage is the reduction of magnet vibrations.

Direct comparison between the two vertical geophones installed on the cold mass has shown systematically larger motion amplitude on the quadrupole (see Fig. 6 and Fig. 7). However, a detailed spectral analysis shows that the difference is due to impact of technical noise sources, such as vacuum pumps, installed with no special care for mechanical isolation. This effect is discovered as soon as these pumps are switched off (see Fig. 8). This is expected since the center of the module is the farthest point from the vacuum vessel supports and from the end caps where external forces are applied and thus damping of the signals at the center is observed. The other feature discovered is that the module center is affected by a mechanical mode with a resonance around 17 Hz, which makes it slightly noisier than the quadrupole, in the frequency band 1-20 Hz. This mode is also visible on the magnet side, both on top of the vessel and on the quadrupole, but with much lower amplitude. This behavior follows the common sense for which the most stable points of a mechanical structure are next to its supports that are nodes for the normal modes.

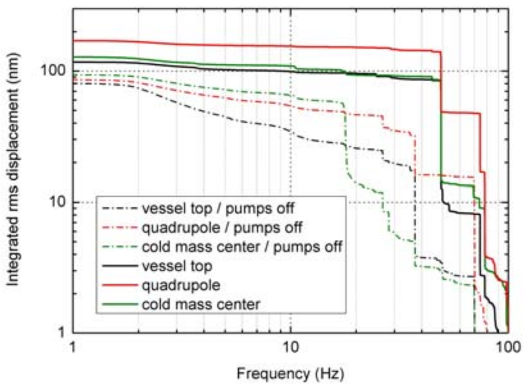

Figure 8: Comparison between the vertical rms displacement measured at 2 K and at room temperature, after switching off the vacuum system. Room temperature data were collected at the same time of the day for consistency.

CONCLUSIONS

Data presented in this work confirm results of the previous studies on Type-II and Type-III and the quality of the mechanical design of the FLASH/XFEL cryomodules in terms of vibration stability. Cryogenic tests have shown vibration levels, measured on the cold mass, are substantially independent of the operational parameters of the inner thermal shield, suggesting benefits from the XFEL layout with respect to the FLASH one. The final word on this issue will be given next year when Module 8 will be installed in the FLASH linac.

As an input for the ILC engineering design, the comparison between seismic sensors installed along the cold mass do not show a clear advantage in terms of vibration stability in moving the magnet package to the center of the cryomodule, once sufficient care for the mechanical isolation of the technical noise sources is taken. At present, the only relevant engineering issue to further improve the quadrupole stability appears to be a proper design of the support of the vacuum vessel to limit the amplification of ground motion, mainly occurring in the horizontal direction transverse to the beam axis, due to rigid body modes of the cryostat.

ACKNOWLEDGEMENTS

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