Quadrupole Vibration Measurements of a TESLA Type II Cryomodule

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Abstract

Results of a study of the mechanical and vibrational features of a TESLA type II cryomodule are presented. The transmission of the ground vibrations to the quadrupole of the so-called 'Superstruktur' has been measured at room temperature, in the frequency range from 0.1 to 250 Hz, using inertial sensors. No evidence for resonances of the quad package support structure has been found within the explored frequency range. A comparison with measurements performed at liquid Helium temperature on an operating cryomodule with similar design is presented. No change in the transfer function is evident in transition from warm to cold conditions.
The TESLA cryomodule mechanical layout, with the quadrupole placed at the end of the module, supported by the Helium Gas Return Pipe (GRP), meets the ILC (International Linear Collider) stability requirements in terms of quadrupole vibration.

1 Introduction

The mechanical design of the cryomodules for the ILC is presently under development [1]. The design is regarded as a further evolution of the cryomodules built with several revisions, for the linac of TESLA and now, for the XFEL project [2]. Nevertheless, except for the proposed new location of the quadrupole package at the center of the module, the main features and layout of the components inside the main cryogenic vessel are preserved for the ILC cryomodule design.

A detailed study of the mechanical and vibrational behavior of the XFEL modules is necessary to provide a basis of understanding for the stability of the ILC cryomodules. It is important to establish a hierarchy of the vibration sources for a standard linac cryomodule, in order to concentrate the design effort on the reduction of the corresponding effects, keeping the design as simple as possible for cost reduction.
Accelerator component vibration spectra are dominated by the effects of near-field sources and by the mechanical features of the support structure as well as 'cultural noise' and ambient ground motion [3, 4]. Near-field sources like electrical motors (vacuum pumps, air-conditioning, fans, compressors etc.), if not properly isolated, produce huge vibrations, well above the site ground motion levels, with peaks in the frequency region between 10 and 50 Hz. This 'facility' noise is transmitted to the accelerator optical components through the floor and then through the girders. The girder system itself, if poorly designed, can produce a large amplification of the ground motion, especially in the horizontal directions [5]. It is easier to design a stiff girder in the vertical direction with high resonant frequencies pushed well above 100 Hz. A cryomodule, whether supported via a girder system on the floor or hanging on the ceiling of a tunnel, may behave like a compound pendulum and peaks, corresponding to the normal modes of the structure, along its different degrees of freedom, could appear in the spectrum of the module motion at frequencies which depend on the girder/support stiffness and on the module mass. Therefore, careful design of a cryomodule girder/support system is needed to push these resonant frequencies to as high values as possible.
Study of the dynamics of TESLA type II cryomodules has been the subject of several investigations in the last few years, using different instruments and setups [6-8]. In this work, support structure of the quadrupole, has been investigated to study the mechanical transfer function from the vacuum vessel to the quad package and to check for internal resonances. The experiment has been performed on a fully equipped test type II cryomodule (Superstruktur) at room temperature. Comparison with a data set measured on the Module 4 at the Tesla Test Facility (TTF) in cryogenic operating conditions has also been presented [7]. With respect to the quadrupole, TTF-Module 4 has the same internal mechanical design as Superstruktur.

2 Superstruktur Cryomodule Measurements

The Superstruktur module, assembled in 2002 at the TTF in DESY, is 12 m long and contains eight 9-cell superconducting Niobium cavities, a cold cavity type beam position monitor and a superconducting quadrupole/steerer package at the end. The string of cavities and the quadrupole package are supported by the 300 mm diameter GRP. The GRP is supported from above by three posts consisting of large diameter thermal insulating fiberglass pipes terminated by two shrink-fit stainless steel flanges. The posts are fastened to large flanges on the upper part of the vacuum vessel by adjustable suspension brackets for alignment purposes

(see [2] for details). The central post is fixed while the two laterals can slide to compensate for the thermal differential shrinkage.
The aim of this design is to provide a very rigid support for the core components of the cryomodule, pushing the resonant frequencies of the system, resulting from the environmental sources of vibration, the ground and the facilities in the tunnel, as far as possible. The quadrupole package is connected to the GRP by two large and stiff ring brackets (one at each end of the Helium vessel) split in halves for easy mounting and alignment (Fig.1).

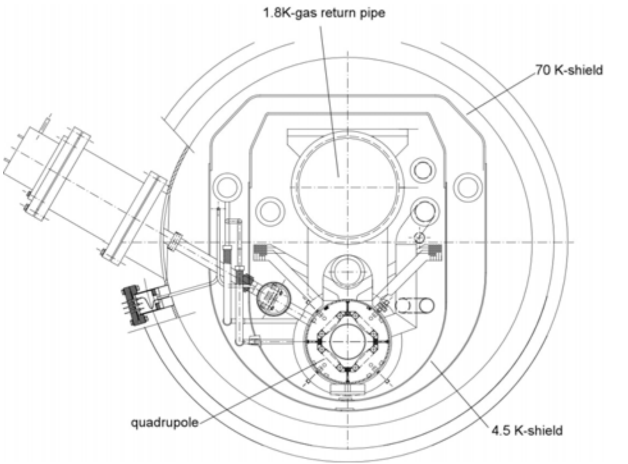

Fig.1 Cross-section of a Type II cryomodule [2]. On the right, a picture of the quadrupole support structure is shown.

Tuners, couplers and current leads provide additional lateral connections from the vacuum vessel to the string of the cavities and the quad package, increasing the stiffness of the structure. The concept of using the GRP as the main structural element for the cryomodule core survived a number of iterations done in the last few years and is still the basis of the ultimate XFEL Type III+ cryomodule design as well as the ILC baseline design [9, 10]. In the latter designs, the cavity string and the quad are fixed to a reference invar rod. The quad is not rigidly fixed to the brackets but sits on cylindrical bearings; this way, during cool down, the quad can just slide on cylindrical bearings preserving the alignment with respect to the cavity string.

2.1 Experimental Setup

In this experiment, vibrational stability of the quadrupole package, both in vertical and horizontal (transverse and longitudinal) directions to the beam pipe, was measured using environmental noise (floor and facility) as sources of vibrations. To cross check the quality of the data and for a better understanding of the dynamical behavior of the structure, transfer functions between the ground and the vacuum vessel, vacuum vessel and the Helium GRP and the Helium GRP to the quadrupole were measured. For this purpose, two broadband triaxial seismometers Güralp CMG-6TD [11] and four single-axis (two horizontal and two vertical) geophones, Model SM-6, manufactured by Sensor Nederland BV [12], were used. The seismometers have a flat response to the velocity from 0.033 to 80 Hz, and a nominal sensitivity of about 1000 V/m/s on each axis. Owing to the force-feedback operation, the device linearity is of the order of 10^{-5} over the whole amplitude range. The seismometers are provided with an anti-aliasing low-pass filter and with a 24-bit digitizer and a sampling rate of 200 samples/s. The digitizers of the two seismometers may be synchronized by using a GPS signal as the reference. In terms of ground displacement, the root mean square (rms) noise integrated above 1 Hz is 0.03 nm for all three axes. The low-noise and high linearity allow for a 0.5% overall accuracy in the readout of the inertial motion, even at nanometer level. The geophones used have a 4.5 Hz spring system and a nominal output of 28.8 V/m/sec. A suitable non-linear amplifier extends their frequency response, from 1.7 to 350 Hz, and makes it flat in the velocity domain. The output of the amplifier, nominally 20000 V/m/sec, is low-pass filtered and then digitized by using a 16-bit ADC at a rate 500 samples/sec. The amplitude accuracy achieved with this device is of the order of 2-3%, with a self-noise of 2 nm rms integrated above 1 Hz [13]. Data from the sensors is continuously transferred to a laptop where FFT (Fast Fourier Transform) for each data set is performed online with custom written software which converts velocity frequency components into displacement. Each data set time length is 60 s for the seismometers and 6 s for the geophones. In order to improve the measurement accuracy, rms average of the spectra was computed. No windowing was applied to the FFT analysis of these measurements.

Fig.2 Superstruktur cryomodule in the Hall 3 in DESY was placed on two concrete slabs (right); Experimental layout, with two seismometers measuring simultaneously, one on the ground, the other on the vessel top (left)

The seismometers were placed on the vessel top, inside the Helium GRP and on the floor (for reference measurement). Each data taking period lasted from 30 minutes to 1 hour on a Friday afternoon, in February 2006, when the experimental hall was quiet. Due to space constraints on the quadrupole, only geophones (both vertical and horizontal) could be placed on the quadrupole. In addition, geophone measurements were taken on the vessel top, inside Helium GRP and the floor for snapshot measurement periods of few minutes, taking data simultaneously with the seismometers (Figs. 2 (left), 3).
In this experiment, the module was placed on two large concrete slabs and the end caps were removed to get direct access to the quadrupole and the GRP (Fig.2, right). In an earlier measurement, in November 2005, the module was clamped to the module assembly stand. Unless stated otherwise, results presented in this report are from Feb'06 measurement period.

The behavior of the girder support is shown in Fig.4, 5 and 6, where the motion of the main vessel is compared with the ground motion. Included in all the PSDs (Power Spectrum Density), are the amplitude ratio functions, i.e. $\sqrt{\mathrm{PSD(Vessel\ Top)}}/\sqrt{\mathrm{PSD\,(Ground)}}$ in each figure. Three large amplitude peaks are clearly visible at 4.3, 8.3 and 9 Hz, while in the horizontal-transverse axis the motion is dominated by the 4.3 Hz mode.
These low frequency, large amplitude resonances could be caused by the girder support of the cryomodule since it was supported on two concrete slabs, with no clamps or bolts. A number

of other peaks, in all the spectra (including the ground) in the range 10-50 Hz (12.6, 24.6, 35.5, 37.6, 48.8 Hz), are produced by vibrating devices in the experimental hall, such as electrical motors.

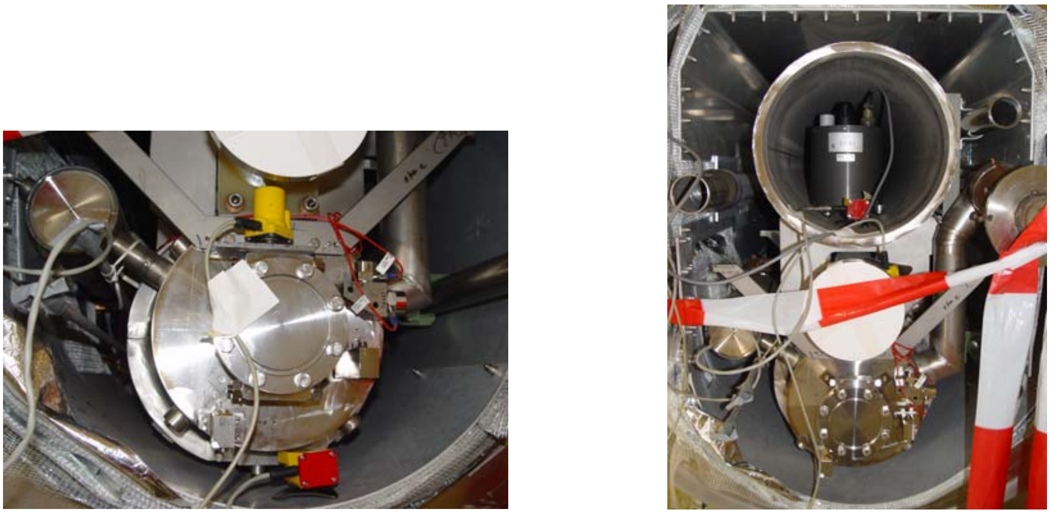

Fig.3 Experimental layout: A vertical geophone was placed on the quadrupole (left). A seismometer was placed inside Helium GRP (right)

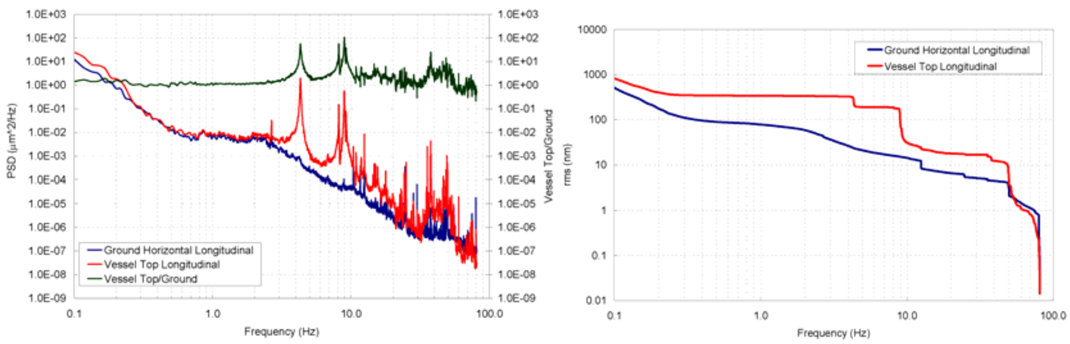

Fig.4 Power spectrum and integrated rms amplitude of the vessel motion compared with the ground in the longitudinal direction. At 1 Hz cut-off, rms motion is 259 nm for the vessel and 65 nm for the ground.

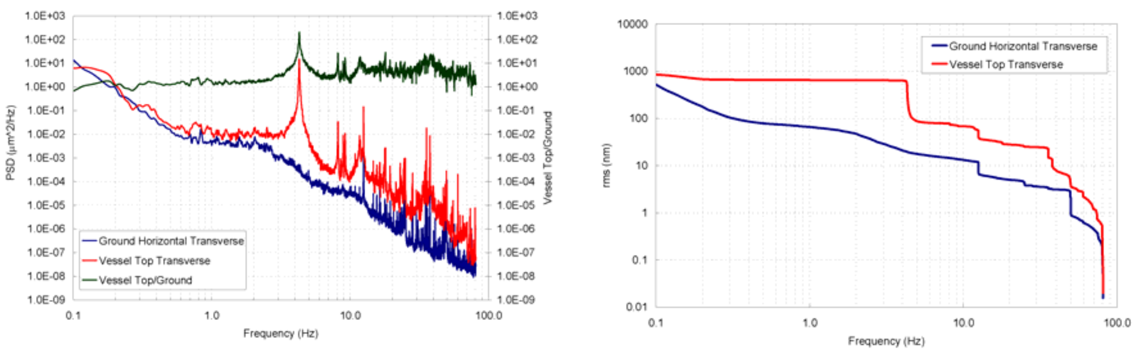

Fig.5 Power spectrum and integrated rms amplitude of the vessel motion compared with the ground in the horizontal transverse direction. At 1 Hz cut-off rms motion is 651 nm for the vessel and 65 nm for the ground.

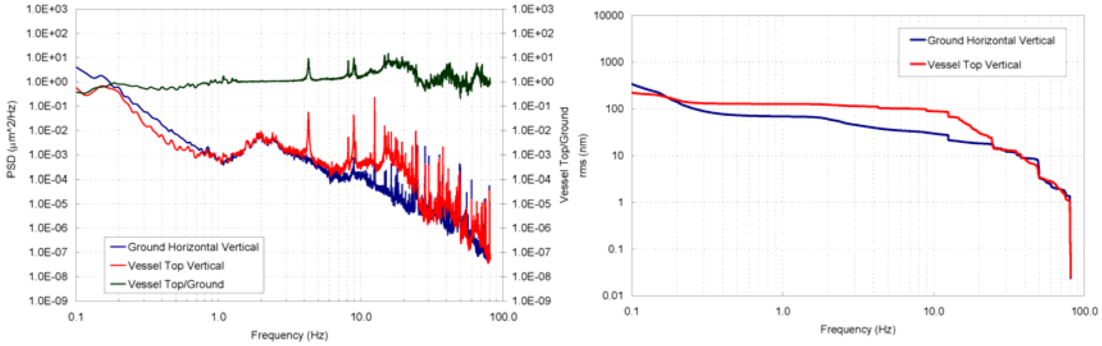

Fig.6 Power spectrum and integrated rms amplitude of the vessel motion compared with the ground in the vertical direction. At 1 Hz cut-off, rms motion is 127 nm for the vessel and 69 nm for the ground.

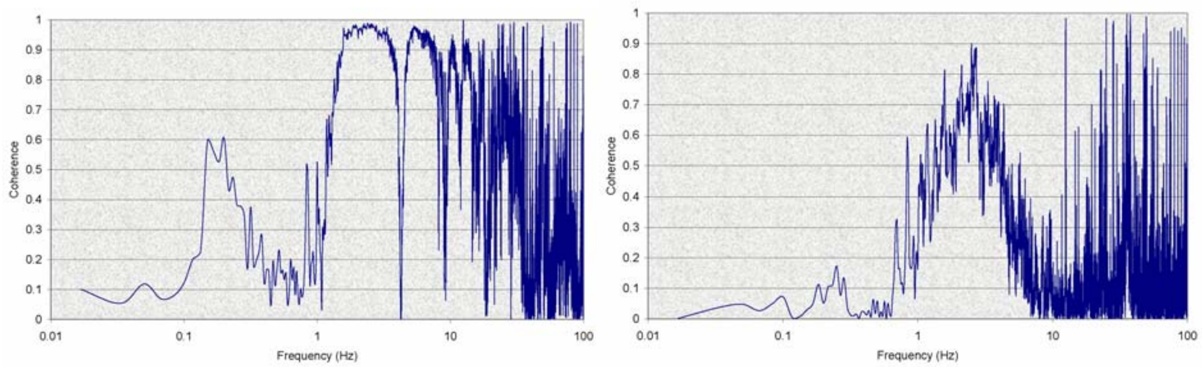

Fig.7 Coherence of vessel top and ground in the vertical direction (left) and horizontal transverse (right)

In the vertical direction, a peak at 4.3 Hz which is due to coupling with the transverse axis can be seen (Fig. 6, left). In order to gain a better understanding of signal to noise ratio in the measured frequency band, coherence function between two synchronized measurements can be calculated. For a definition of coherence please refer to [14, 15].
Coherence plot for the vertical direction shows zero coherence at this frequency (Fig. 7, left) indicating that vertical motion on the vessel is not produced by the vertical vibration of the girder/ground, but the horizontal motion.

2.2 Vessel to GRP Connection

Rigidity of the vessel to the GRP connection was tested by placing a seismometer on top of the vessel and another seismometer, inside the GRP. In the horizontal transverse axis, (Fig.8) a very good agreement between the two spectra over the 0.1-15 Hz band is found. This is also seen in the corresponding coherence plot (Fig. 9). In this frequency range, the vessel and the GRP move together with an amplitude ratio of He GRP/Vessel Top~0.86 . The PSD spectra and the amplitude ratio functions show that there is no signature of internal resonances in the vessel-He GRP structure.

At higher frequencies, environmental background noise dominates and the motion is uncorrelated, as shown by the coherence function spectra in Fig.9 for both measured directions.

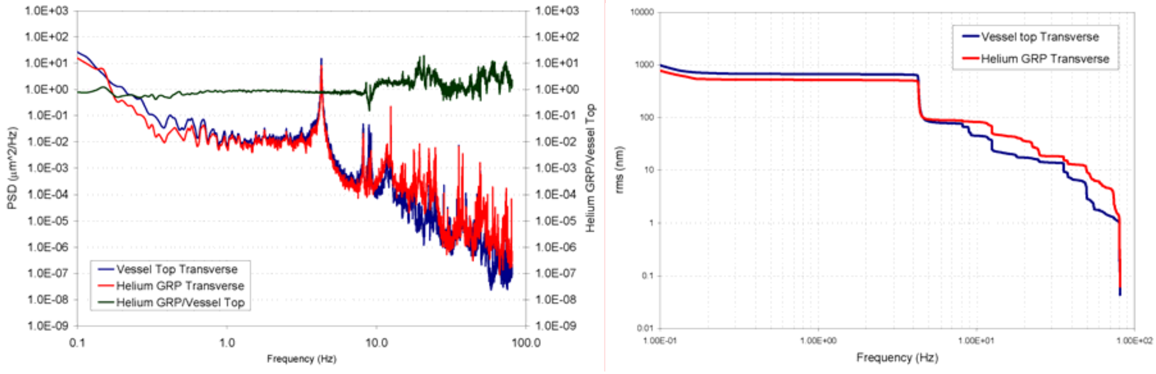

Fig.8 Power spectrum and integrated rms amplitude of the motion of the main vessel and the Helium GRP in the horizontal transverse direction. At 1 Hz cut-off, rms motion is 592 nm for the vessel and 510 nm for the Helium pipe.

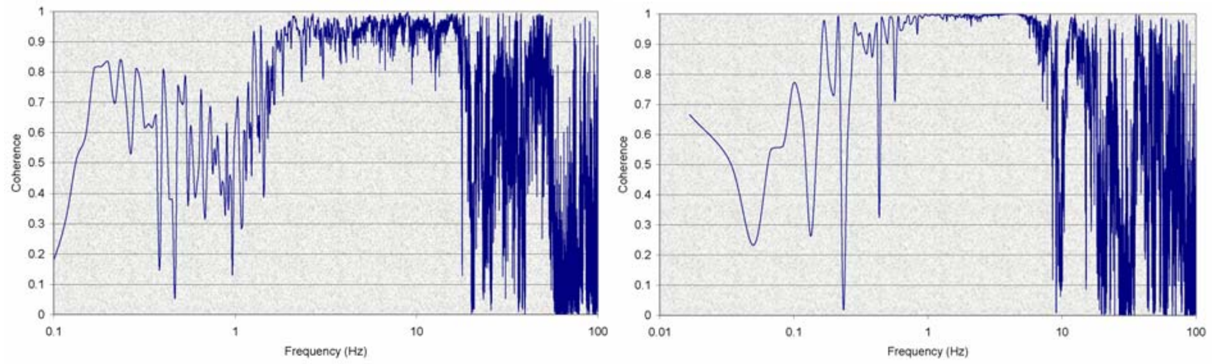

Fig.9 Coherence between the vessel top and Helium GRP, Left: in the vertical direction, good coherence exists up to 18 Hz, right: horizontal transverse direction to the beam pipe (good coherence signal up to 8 Hz)

The difference between the integrated rms above 1 Hz (Fig.8, right), including both coherent and incoherent parts, corresponds to ~20% of the amplitude of the two signals (larger at the top of the main vessel).

In the vertical direction (Fig.10), a similar behavior as for the horizontal direction is observed. There is good agreement between the two spectra (vessel top and He pipe) up to 18 Hz and low coherence in the 20-40 Hz band (Fig.9, left). In this case, the integrated rms motion calculations (Fig.11, right) show a relative amplitude difference of ~ 30% (176 nm vs. 123 nm) integrating from 1 Hz, larger on the GRP. No internal resonance of the structure is visible on the spectrum as seen from the transfer function $\sqrt{\text{PSD(Helium GRP)}} / \sqrt{\text{PSD (Vessel Top)}}$ (Fig10, left).

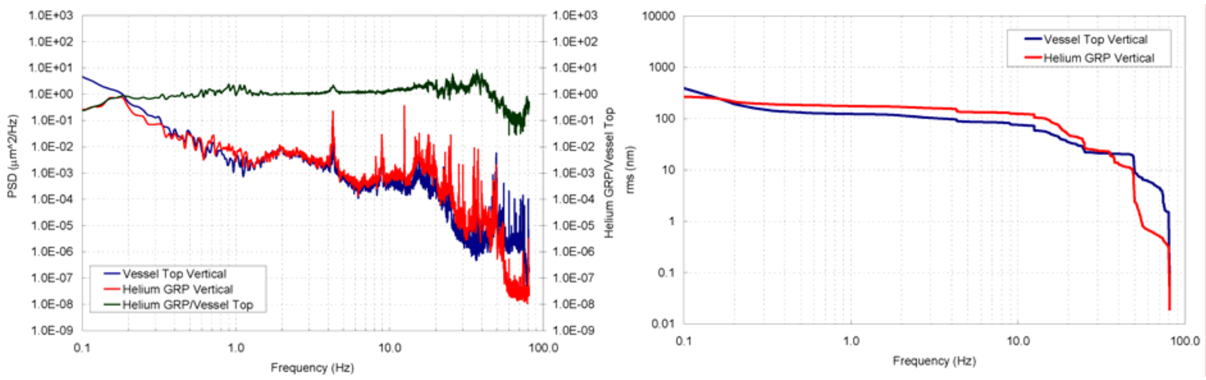

Fig.10 Power spectrum and integrated rms amplitude of the vessel compared with the Helium GRP in the vertical direction. At 1 Hz cut-off, rms motion is 123 nm for the vessel and 176 nm for the He GRP.

2.3 Quad to GRP Connection

Measurements of relative motion between the quadrupole and the Helium GRP were performed by using geophones because of the small space available on the quadrupole. The spectra and the amplitude ratio functions are shown in Figs. 11 and 12 in the case of horizontal transverse (Nov'05 measurement) and vertical (Feb'06 measurement) directions respectively.

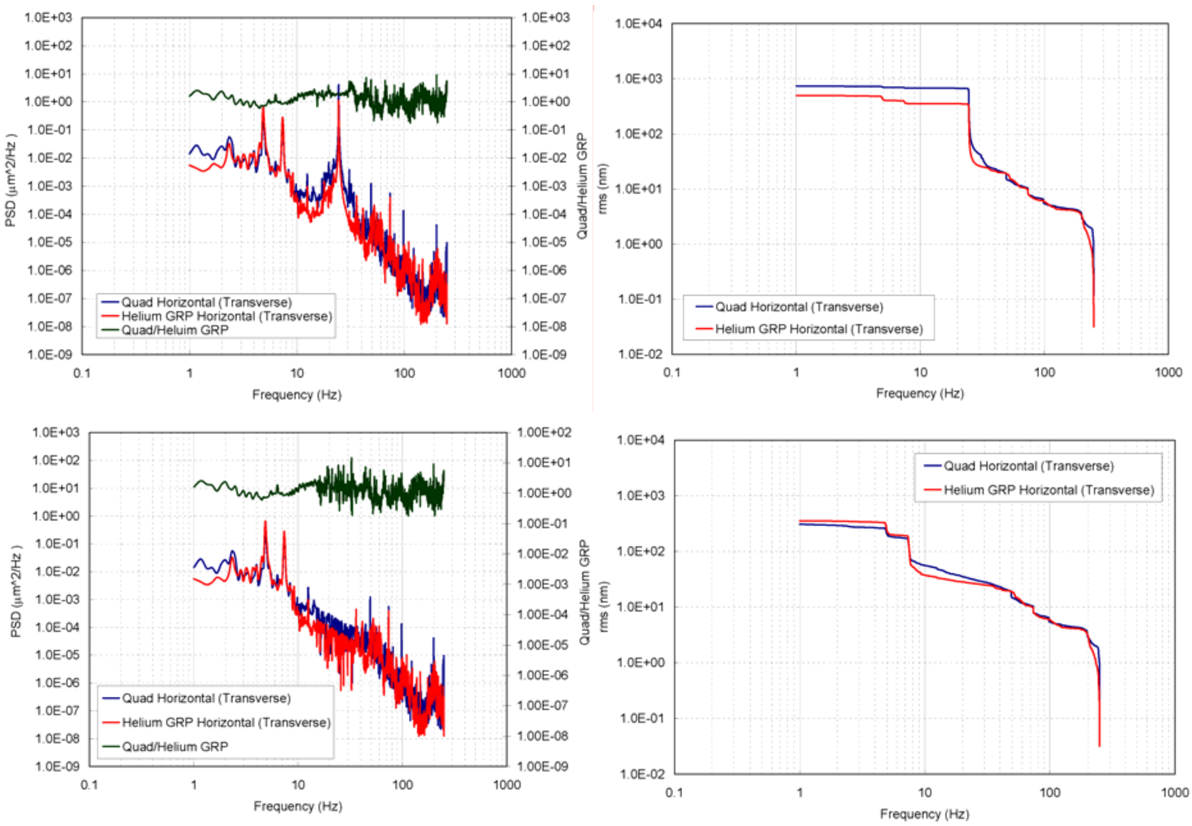

Fig.11 Power spectrum and integrated rms amplitude of the quadrupole compared with the Helium GRP in the horizontal transverse direction. The plots in the first row, show a peak at 24.5 Hz, due to facility noise in Nov'05 measurement. In the second row, the same plots are shown but in this case, the peak at 24.5 has been filtered out. At 1 Hz cut-off, rms motion is 298 nm for the quadrupole and 352 nm for the He GRP.

The peak at 24.5 Hz (Fig. 11, top row, left), is due to moving motors in the vicinity of the cryomodule and it can also be seen in the ground spectra. Owing to the response function of the geophones (see section 2.1), f ~2 Hz was the cut-off frequency for the integrated rms motion. The integrated rms vibration (Fig. 11, top row, right) is 750 nm on the quad and 506 nm in the GRP; in other words, 1.5 times more vibration is seen on the quad because of a nearby noise source. In Fig. 11 (bottom row, left), the peak at 24.5 was filtered out and the resultant PSD were integrated to obtain rms motion.
The integrated PSD at f > 2 Hz, Fig.11 (right), shows that the ratio of the movement of the He GRP/Quad is 1.18. In other words, the He GRP-quad package is rigid to within 20% in the horizontal transverse direction. In both plots, there are no signs of mechanical resonances from the support bracket structure up to 250 Hz. However, this result shows that it is imperative to isolate sources of facility noise from the cryomodule.

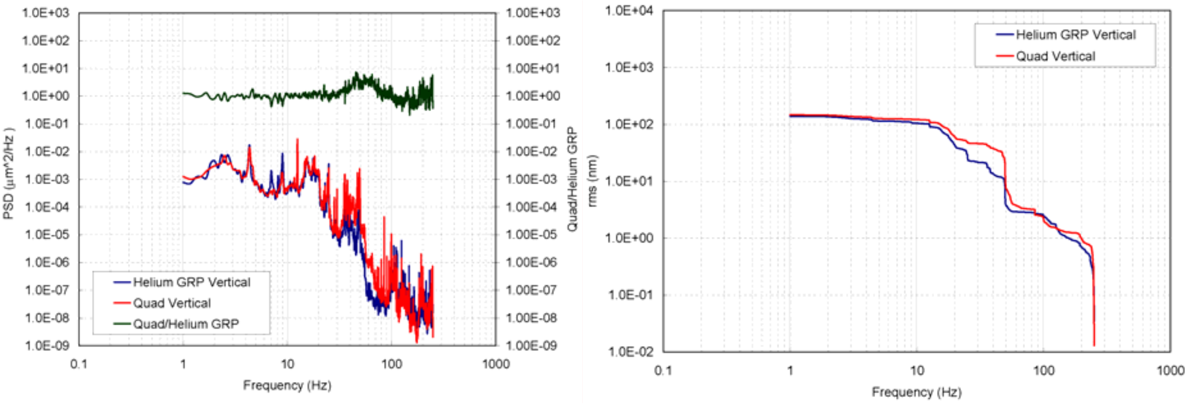

Fig.12 Power spectrum and integrated rms amplitude of the quadrupole compared with the Helium GRP in the vertical direction. At 1 Hz cut-off, rms motion is 148 nm for the quadrupole and 140 nm for the He GRP.

In the vertical direction, the integrated PSD at f > 2 Hz, for the ratio of He GRP/Quad turns out to be 0.94. In other words, the He GRP-quad package is rigid to within 10% in the vertical direction.
In order to compare the rigidity of vessel top vs. quadrupole package, in the vertical direction, the geophone measurement on the quadrupole is plotted with the seismometer measurement on the top of the vessel (Fig. 14) taking into account the differences between seismometer and geophone data set. A difference of ~ 10% is seen in the rms motion of vessel top with respect to the quad, confirming the rigidity of the vessel top-quad package.

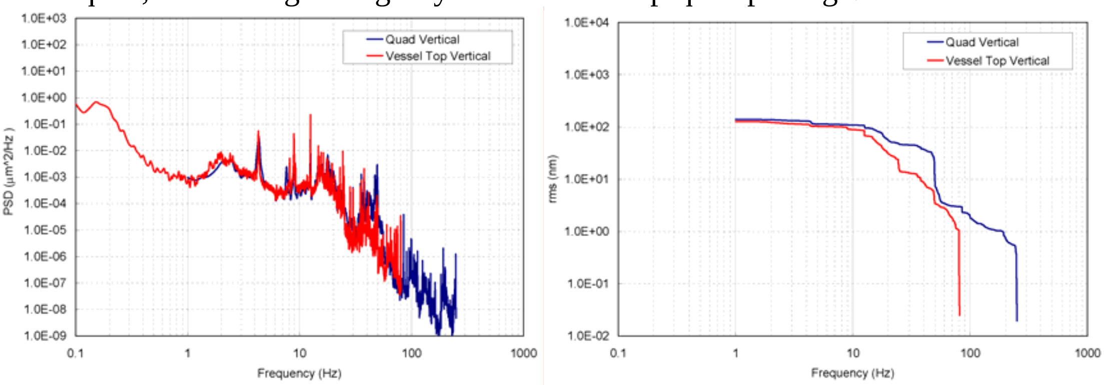

Fig.14 Power spectrum and integrated rms amplitude of the vessel compared with the quadrupole in the vertical direction. At 1 Hz cut-off, rms motion is 127 nm for the vessel top and 140 nm for the quadrupole.

Table 1 shows integrated PSD at f > 1 Hz (in the case of a seismometer measurement) and f > 2 Hz (in the case of a geophone measurement) at different locations of the cryomodule.

	Vertical (nm)	Horizontal (Trans.)	Horizontal (Long.)
Vessel top/Ground	127/69	651/65	259/65
He GRP/Vessel top	176/123	510/592	568/449
Vessel top/Quad	127/140	482/421 (estimation)	342/277
He GRP/Ground	183/84	564/79	341/78
He GRP/Quad	135/144	352/298	210/326
Quad/Ground	141/58	N/A	326/51

Table1: rms vibration ratios at different points of the cryomodule package at f > 1 Hz (seismometer data) and at f > 2 Hz (geophone data)

3 TTF Module 4 Measurements in the Cryogenic Conditions

In this section, results of the vibration measurements on a Type II cryomodule (module 4) in normal cryogenic operation in the linac of the TTF are presented. This data has already been published [7] but is presented here for comparison, since firstly, the two data sets were obtained on the same mechanical structure; both ‘Superstruktur’ and module 4 are of Type II design. Secondly, vibration measurements at room temperature (in this case, ‘Superstruktur’) could be compared with measurements at 2K (Module 4 incorporated in the linac of the TTF) even though the sensors used for each measurement had different frequency response range.

3.1 Experimental Setup

Six charge-mode piezoelectric accelerometers were used at three positions in module 4, each pair, measuring horizontal transverse and vertical directions: two Bruel & Kjaer 8318 [16] were placed on the elbow structure hosting the levelling foot of the module, four Endevco 7703A-1000 [17] were placed respectively on top of the cryomodule and in the cold on the quadrupole. The output of the piezo accelerometers was converted to a voltage proportional to the acceleration by using Bruel & Kjaer 2635 signal conditioners. An additional vertical SM-6 geophone was placed on the same socket as the calibration reference, since piezo’s calibration accuracy is only ±10% according to the specifications. In particular, for the two piezo’s operating in the cold, a re-calibration factor of 3.15 was applied to compensate for the huge loss of sensitivity at cryogenic temperatures. In this report, data measured on the elbow structure is not presented because it is not comparable with the Superstruktur data set. All the channels were digitized using a 16-bit ADC at a rate of 500 samples/s. The measurements lasted for two hours around midnight and consist of 720 time series of 10 seconds each. The spectra shown are the result of the rms average over the whole data set. Typical ground motion level in the TTF tunnel measured with a Güralp CMG-3T seismometer nearby Module 4 is shown in Fig.15 as a reference. The integrated rms amplitude at f > 1 Hz, is about 50 nm

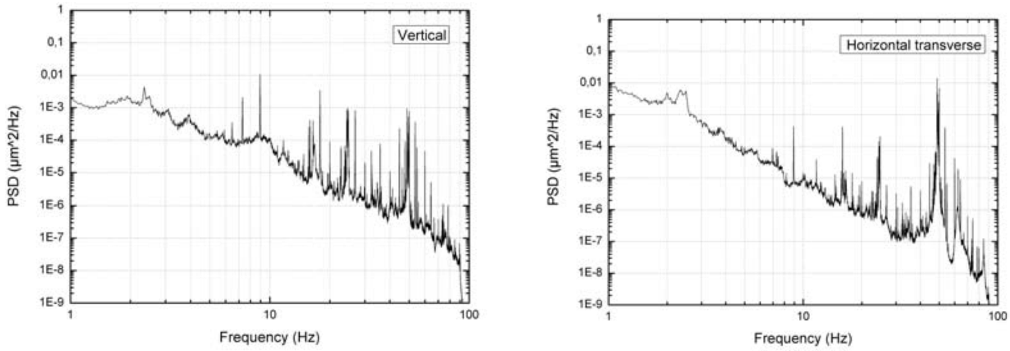

Fig.15 Floor motion at the TTF measured around midnight in the vertical (left) and horizontal transverse directions (right).

in the vertical and 65 nm in both horizontal directions. Specifically, the two large peaks at 24.6 and 48.8 Hz might be due to the insulation vacuum pump and its frequency converter (rotating transformer) in the vicinity of the measurements.

3.2 Cold Quadrupole Vibrations: Horizontal Transverse

The PSD spectra of the vessel top and the quadrupole (measured at 2K) in the horizontal transverse direction and the amplitude transfer function, $\sqrt{\text{PSD(Vessel Top)}} / \sqrt{\text{PSD (Quad)}}$ are shown in Fig. 16, left. These spectra are possibly dominated by the effects of the local vibration sources both directly connected to Module 4 and elsewhere along the linac structure and bridged to Module 4 through the bellows. The peak at 10.4 Hz present in both spectra is most probably a resonance of the girder support system, but the peak at 12.5 Hz is also seen in the floor PSD spectra and is due to facility noise.
The corresponding coherence plot between the vessel top and the quad (Fig. 17, right) shows that the piezo sensors are noisy below 7 Hz and hence, the measurement will be affected by the piezo sensor limitation at $f < 7$ Hz. The integrated rms amplitude (Fig 16, right) is larger for the cold-mass by 50%, 120 nm against 80, if one reads the integrated rms values around 7 Hz. However, no internal resonances are found in the vessel top-quad package at 2 K as seen from the amplitude transfer function (Fig. 16, left).

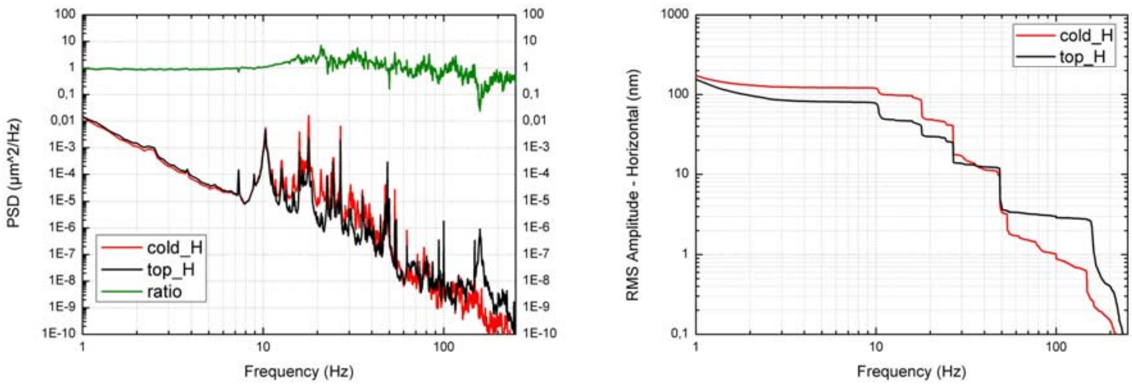

Fig. 16 Comparison between the PSD measured on top and on the cold mass in the horizontal transverse direction perpendicular to the beam line (left) and the corresponding integrated PSD at a cut frequency of $f > 1$ Hz (right)

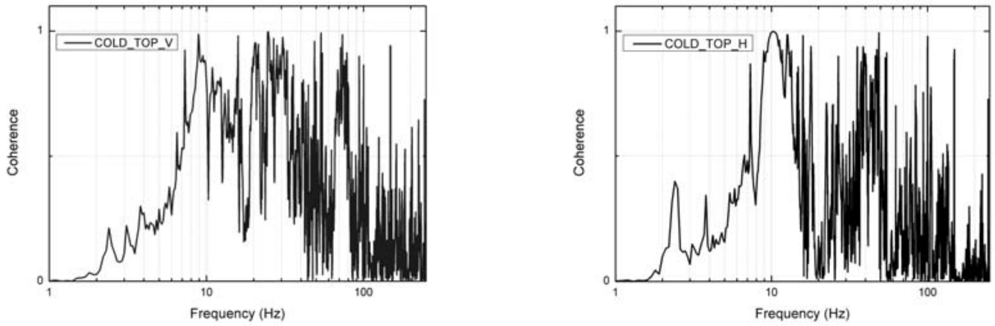

Fig. 17 Coherence between the top vessel (warm measurement) piezo accelerometer and another one placed on the cold mass (cold measurement) in the vertical direction (left) and in horizontal transverse direction (right). The coherence drops down (<0.5) below 7 Hz showing the limit performance of the charge mode piezo sensors.

3.3 Cold Quadrupole Vibrations: Vertical

PSD spectra in the vertical direction, together with their corresponding amplitude ratio function for the vessel top and the quad (at 2K) are shown in Fig. 18. Again, no evidence of internal resonances is found in the vertical direction, proving the rigidity of the quad support design. The integrated rms amplitude above 7 Hz, as shown in Fig. 18, right, is larger on the quad (at 2K) compared with the vessel top by 40%, i.e. 70 nm vs. 50 nm respectively.

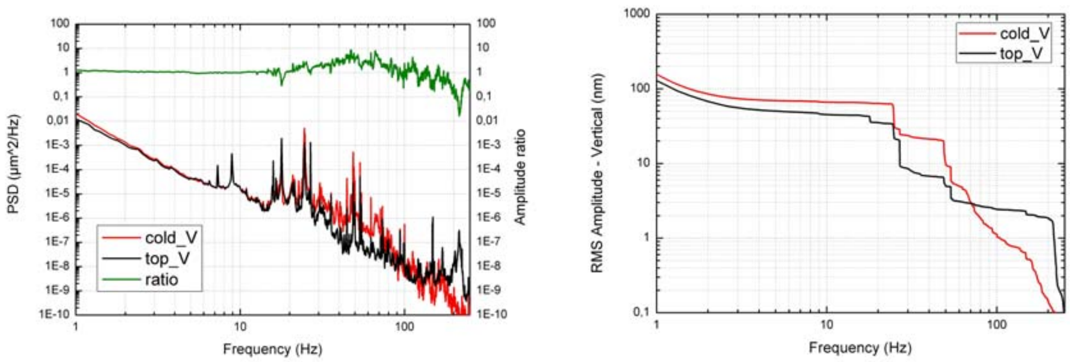

Fig. 18 Comparison between the PSD measured on top and on the cold mass in the vertical direction (left) and the corresponding integrated PSD at a cut frequency of f > 1 Hz (right)

3.4 Cold Mass Investigation Plan

As the coherence signal of piezo accelerometer shows (Fig 17), piezo measurements are unreliable below 7 Hz. Therefore, for the study of the ILC quadrupole stability in the cold, more investigation is necessary to evaluate possible excess quadrupole vibrations produced by the Helium gas flow in the GRP, at 2K. In addition, a higher heat load from the cavities is expected to be produced which may affect quadrupole stability at 2K. This was not investigated in the TTF module 4 measurement at 2K. For this purpose, optical interferometric techniques will be employed to measure quadrupole vibrations at 2K. Modules 8 and 9 for the XFEL, now under construction, will be equipped with optical access through view ports. Two lines of sight, one for the vertical axis one for the horizontal transverse axis, are opened through the two thermal shields allowing a laser beam to hit two small retroreflectors rigidly mounted on the quadrupole Helium vessel. The motion of the quadrupole with respect to the module vacuum vessel will be measured to precisely evaluate whether vibration is introduced by the cryogenic system. The reference mirror of the interferometer will be placed on a support rigidly connected to the module vessel. In order to discriminate this relative motion from the absolute motion of the cryomodule, a witness geophone or seismometer will be hosted on the same supporting structure.

Summary

Results presented in this report can be summarized as follows:

- In the low frequency range, less than 10 Hz, the cryomodule and its core move as a whole, as the amplitude ratio functions computed from the PSD spectra show. In this frequency band, dynamics may be influenced by the quality of the module supports.
- The vibration spectra are affected by the facility noise.
- Substantial agreement between the dynamics of the cryomodule vessel and the quad package was found in both axes; no evidence for resonances of the quadrupole support structure were discovered in the explored frequency range 0.1 to 250 Hz, proving reliability of the design.
- The performance of the available charge mode piezoelectric accelerometers used in this experiment, for the cold measurements, is limited below f ~ 7 Hz as shown by their coherence function; while at higher frequencies they may be reliable.
- Comparison between integrated rms of the PSD measured at two locations (vessel top and on the quad at 2K) show a larger amplitude on the cold mass, by 50% in horizontal and 40% in the vertical direction at a cut frequency of f > 7 Hz. In both cases, the difference is produced in the frequency range 10-50 Hz.
- Results are consistent with the measurements in the room temperature, as no clear effect on the quarupole stability, due to vibrations, in the cryogenic conditions were observed.

4 Conclusions

A detailed investigation on the vibrational behavior of cryomodules has been presented. By accurately measuring the relative motion between different parts of the module with inertial sensors, transfer function from the cryomodule main vessel to the quadrupole was evaluated. The measurements have been compared with an existing data set taken in the cold (at 2 K) for Module 4 at the TTF. Despite different experimental conditions (Module 4 was integrated in the operating linac), the results on the stability of the quadrupole support are consistent. No clear evidence for resonances of the quad package support structure has been found in the frequency range up to 250 Hz, both in the vertical and horizontal transverse directions. The design where the quadrupole is supported by the Helium GRP seems to be rigid and free of internal resonances.
Nevertheless, design effort must be rather concentrated on the girders and on the module isolation from facility noise present in the tunnel that otherwise would dominate dynamics of the module itself.

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