EFFECTS OF THE CRYOGENIC OPERATIONAL CONDITIONS ON THE MECHANICAL STABILITY OF THE FLASH LINEAR ACCELERATOR MODULES

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Abstract

The superconducting linear accelerator (linac) of the European X-ray Free Electron Laser (XFEL) XFEL will nominally operate with 0.65 ms long, widely spaced (~200 ns) electron bunch trains, at a pulse repetition rate of 10 Hz [1]. Tight tolerances on energy and position jitter of the 17.5 GeV electron beam, 0.01 % and 10 % of the beam size respectively, are demanded for the operation of the photon beam section of the accelerator. Feedback systems are foreseen upstream of the undulators to keep these beam instabilities, produced by a variety of sources, within the specifications. Mechanical vibrations of superconducting quadrupoles and cavities are amongst the most relevant. In this work, we present results of a systematic investigation carried out during several months of beam operation of the Free electron LASer in Hamburg (FLASH), using a network of moving coil seismometers (geophones). Results of a preliminary study on the impact of large levels of cavity microphonics on the accelerating field stability are also reported.

INTRODUCTION

Knowledge of the limits achievable, during real operation, of the mechanical stability of the superconducting accelerating modules (cryomodules), hosting accelerating cavities and quadrupoles, is important for the engineering design of the XFEL. The uncorrelated fast motion of the superconducting quadrupoles, generated by ground vibrations and technical systems (vacuum and cryogenics), is considered to be the largest cause of pulse-to-pulse beam position jitter at the end of the linac. Minor contributions are expected, in order, from the ripple of magnet power supplies and from energy jitter / dispersion [2]. Measurements carried out at DESY on stand alone operating Type-III cryomodules [3] have shown that vibration levels close to the site ground motion are achievable on the quadrupoles in the 1-100 Hz frequency band. Four cryomodules in the FLASH linac have been recently instrumented with geophones, allowing for the first time to investigate, on a larger scale, the effects of the cryogenic operational conditions on the mechanical stability of the accelerator components and hence, on the electron beam parameters. Vibrations of quadrupoles, vacuum vessels and local ground have been continuously recorded since November 2007, providing real time information on the status of the linac. Root mean square (rms) levels and spectral characteristics of the mechanical noise have been investigated for a number of different configurations of the cryogenic plant.

VIBRATION SURVEY IN FLASH

The quadrupoles of Type-II cryomodule ACC3 and of the string of three Type-III modules ACC4, ACC5, ACC6 (see Fig. 1) have been equipped with single axis vertical geophones GS-11D type from Oyo Geospace [4]. These devices have demonstrated reliable operation down to 4.5 K with no loss of sensitivity, and remote calibration capability. Identical sensors in horizontal (oriented in direction transverse to the electron beam axis) and vertical configuration were installed on top of each vacuum vessel as room temperature reference channels.

Two additional horizontal / vertical pairs were placed on the ground of the facility, underneath ACC3 and ACC5, as environmental channels providing amplitude and spectral information on the seismic activity of the site (see an example in Fig. 2). The response of the geophones has been extended down to ~ 0.7 Hz with non-linear inverse filtering; an equivalent displacement noise level around $1\,\mathrm{nm}/\sqrt{\mathrm{Hz}}$ at 1 Hz is achieved after digitization with a 16 bit ADC (Agilent U2300).

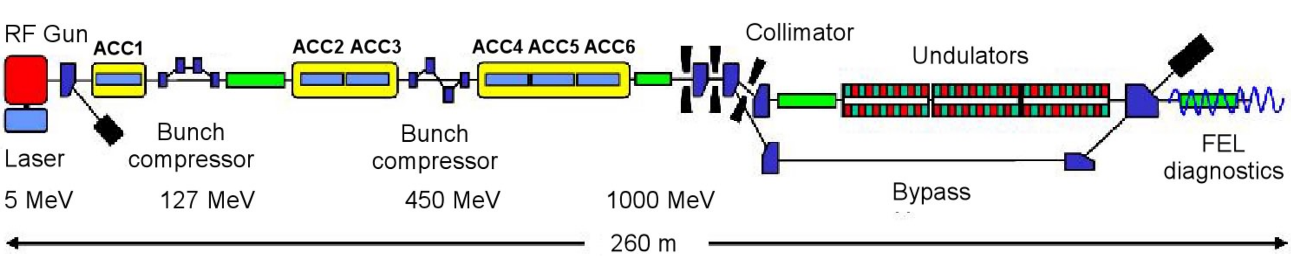

Figure 1: Layout of the FLASH facility; six cryomodules, with eight TESLA-type cavities each, accelerate the electron beam up to 1 GeV. Laser pulses with wavelength as short as 6.5 nm are produced at 10 Hz repetition frequency by Self-Amplification of Spontaneous-Emission (SASE) radiation in the undulator section.

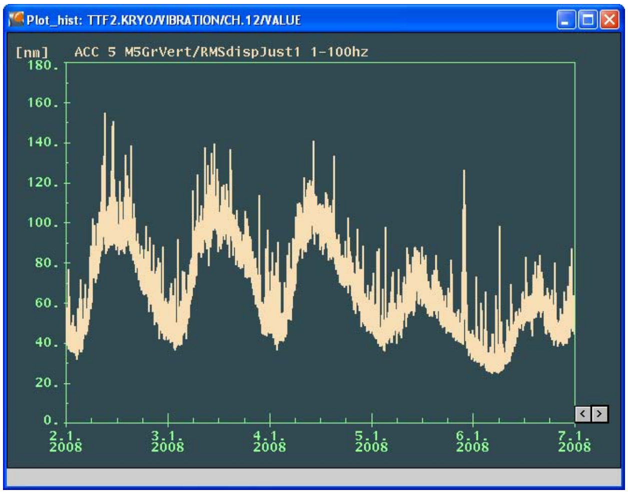

Figure 2: Typical weekly rms amplitude history from the DOOCS server as measured on the ground of the FLASH tunnel. The strong influence of the traffic noise is clear from the day / night, working / weekend day alternation.

The data for all channels are sampled at 200 S/s and continuously read-out in one second blocks by a PC running a Visual Basic 6 program written as a TINE [5] server and integrated in the FLASH DOOCS [6] control system. For on-line displays in the control room, each second, the server analyzes blocks of data of different lengths (1, 10, 20 s), calculating displacement power spectral densities (PSD) and integrating the displacement over various frequency intervals (1-100 Hz, 20-40 Hz, etc.). This analysis provides data for trend charts, to correlate vibration amplitudes to other accelerator parameters. These data are permanently archived in the FLASH TINE archive and are collected by DOOCS servers for display in DOOCS history panels. For off-line analysis, the raw data are stored in a local disk in binary format in TINE local history files. A client program allows recovering past history, recalculating spectra and reconstructing single events of interest.

STABILITY OF QUADRUPOLES

A strong sensitivity to the changes in the settings of the 4.5 K circuit has been observed for the vibration level measured on the superconducting quadrupoles (see an example of a recent test cycle in Fig. 3). In the FLASH cryoplant layout, all the modules from ACC2 to ACC6 are connected in series with transfer lines across the second bunch compressor. A single series circuit feeds all the quadrupoles with highly pressurized He coolant at 4.5 K.

The return line of the same circuit is used to refrigerate the inner thermal shield. The inlet pressure can be regulated to establish two phases or single phase He; both regimes have been experienced also combined with different flow rates. Three characteristic behaviors have been observed (see Fig. 4 and Fig. 5). In two phases regime, low pressure (1.5-1.7 bar), quiet operation is achieved with noise spectra shaped at low frequency (1-10 Hz) by the DESY site ground motion, and at higher frequencies by technical noise sources, with the strongest line coming from the insulation vacuum pumps.

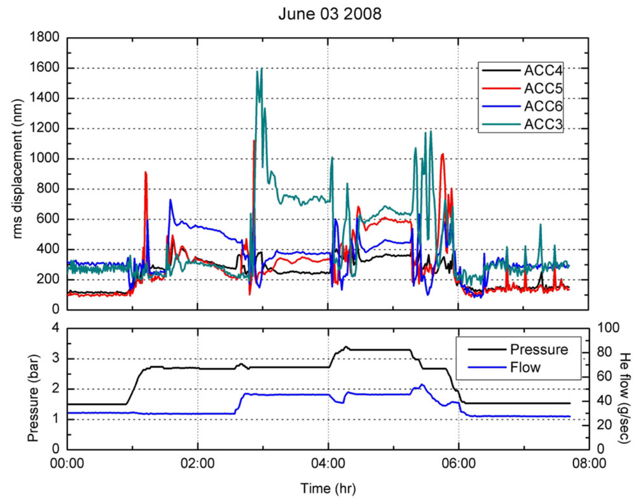

Figure 3: Example of the response of the vibration level measured on the quadrupoles for each monitored cryo-module to the changes in the 4.5 K circuit parameters.

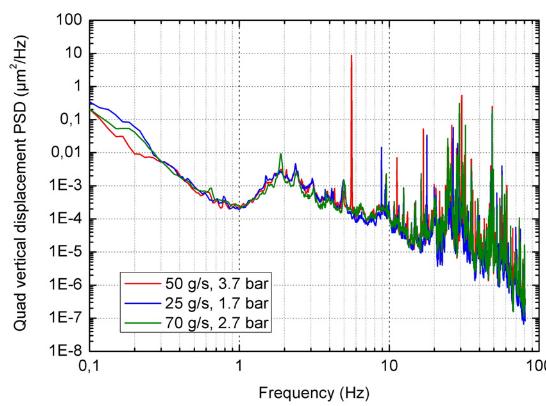

Figure 4: PSD spectra measured on the quadrupole of ACC4 in three selected He flow conditions; all the spectra were collected between 0 AM to 4 AM for consistency.

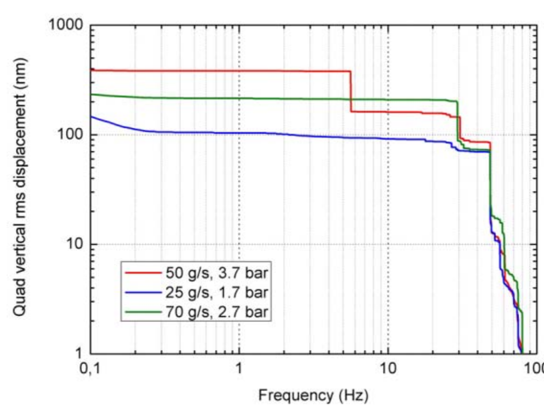

Figure 5: Corresponding integrated rms displacement.

At intermediate pressures, up to 3.3 bar, the He flow becomes unstable and a strong anharmonic vibration at ~ 30 Hz frequency along the whole linac is observed. The amplitude in each cryomodule, ranging from 200 nm to one micrometer rms, even though quite reproducible for every set of cryogenic parameters, does not show any systematic dependence on pressure and flow. At higher pressures, more than 3.3 bar, a low frequency pressure instability is also developed around 5.5 Hz. In this case, ACC3 and ACC4 are the most affected and a rapid decrease of the amplitude of this spectral line is observable in ACC5 and ACC6. It's important to point out that the observed large vibrations introduced by the 4.5 K circuit might not affect XFEL cryomodules in which the quadrupoles will operate at 2 K without direct mechanical connection with the inner shield feed line.

STABILITY OF CAVITIES

After Lorentz detuning compensation with RF feedback / feedforward, as in FLASH, or using fast piezoelectric tuners, as planned for the XFEL, the residual pulse to pulse field stability in the accelerating cavities is affected by frequency detuning caused by mechanical accelerations (microphonics). Cavity on-board vibration amplitude measurement is possible in the three FLASH cryomodules (ACC3, ACC5, ACC6) equipped with fast piezo tuners. The mechanical system cavity+piezo tuner is in fact equivalent to a piezoelectric accelerometer sensitive along the cavity axis, even though un-calibrated, as confirmed by comparison with geophones (see Fig. 6).

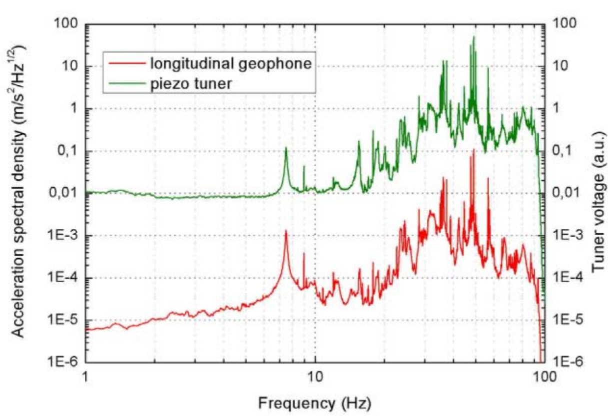

Figure 6: Comparison between the longitudinal acceleration of a cavity, measured with a geophone, and its piezo tuner output voltage. The test was performed on the cavity horizontal test stand at DESY.

In a preliminary experiment, large amplitude vibrations have been induced on the cold masses by selecting suitable sets of parameters in the 4.5 K circuit. Root-mean-square voltage levels from the tuners have been compared with the RF phase jitter of the cavities. For this measurement, RF feedback and feedforward on klystrons were switched off. A clear correlation between mechanical acceleration level and phase jitter has been found (see Fig. 7), however, the induced instability was not large enough to affect the operation of the machine.

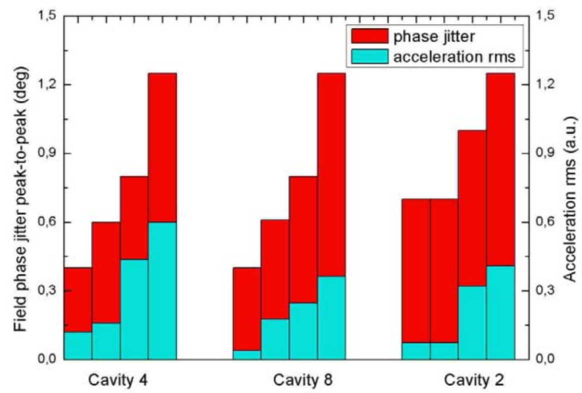

Figure 7: Correlation between the phase jitter in a few selected cavities of ACC6 and the mechanical noise level measured using the piezoelectric tuner as sensor.

CONCLUSIONS

The collected data and the matured operational experience provide a useful reference for the XFEL engineering design and for beam dynamics studies. The so-configured vibration monitoring system, integrated in the control / data acquisition system of the machine, has also proven to be a very useful tool for the diagnostics and parameter optimization of the cryogenic plant.

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