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The Effect of Cooling Water on Magnet Vibrations

S. Redaelli ,R.W. Aßmann, W. Coosemans, W. Schnell

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THE EFFECT OF COOLING WATER ON MAGNET VIBRATIONS

S. Redaelli*, R.W. Aßmann, W. Coosemans, W. Schnell, CERN, Geneva, Switzerland

Abstract

The quadrupole magnets in the CLIC Test Facility II (CTF2) incorporate a water cooling circuit. In the framework of the CLIC stability study, the mechanical vibrations of the magnets were measured for different flows of cooling water. We present the results and compare them with simple theoretical estimates. It is shown that the vibration requirements of the Compact LInear Collider (CLIC) quadrupoles with cooling water can basically be met.

1 INTRODUCTION

Stabilization issues are one of the main concerns for the new generation of Linear Colliders. For instance, tolerances for uncorrelated RMS vertical motion above $4\,\mathrm{Hz}$ for the linac quadrupoles of the Compact LInear Collider (CLIC) [1] are $1.3\,\mathrm{nm}$ [2]. The circulating water used to cool the magnets is a source of mechanical vibrations. In the framework of the CLIC Stability Study, measurements have been done to quantify this effect for the quadrupoles of the CLIC Test Facility II (CTF2) [3], which have a similar design to the ones foreseen for the CLIC linac. In this paper we present the preliminary results of quadrupole vibrations versus water flow. These measurements have been done by means of the active stabilisation system `Stacis2000`, described in details in [4]. This system is used to isolate the motion of the quadrupole from the ground motion, but is not capable of damping vibrations generated by the quadrupole itself. It is thus suitable for studies of water induced vibrations. Other studies about the effect of the circulating water on RF structures have been done at SLAC, as reported in [5].

2 EXPERIMENTAL SET-UP

A scheme of our experimental setup and the cross section of the CTF2 quadrupole [6], with its transverse dimensions, are given in Fig. 1. Each quadrupole is 80 mm long, 6.7 kg weight and has four copper coils made of six rectangular cables, with a 3 mm diameter hole for the cooling water to circulate. Each quadrupole has one feeding channel. Two magnets forming a doublet sit on a common support plate and have independent water connections. The doublet used in our measurements was connected to the regular Geneva tap water system (pressure of about $4\,\mathrm{bar}$). The water was first brought from the tap to a 4 channel manifold and then to the quadrupoles with tubes of different diameter (see Fig. 1). The water volume rate was measured with a precision of 1%. The maximum water velocity in quadrupole pipes was of about $3\,\mathrm{m\,s^{-1}}$ (the nominal value for the CTF2 quadrupoles is $1.2\,\mathrm{m\,s^{-1}}$ [6]).

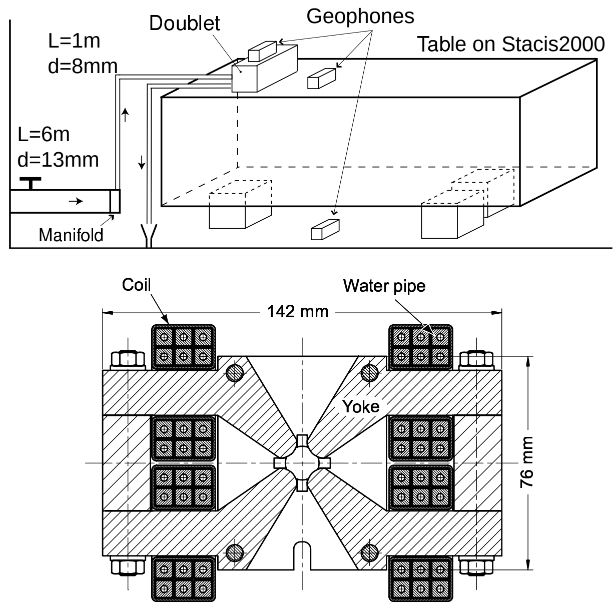

Figure 1: Cross section of the CTF2 quadrupole with its transverse dimensions. In our measurements we used a quadrupole doublet installed as shown in the scheme.

The doublet was fixed directly on top of a honeycomb table, which was supported by actively stabilised feet (see Fig. 1) [4]. Three triaxial geophones of the type described in [4] ($\sim 1\,\mathrm{Hz}$ to $315\,\mathrm{Hz}$ frequency range) were fixed on top of the doublet, on the table and on the floor. Geophones provide a measure of the mechanical vibration velocity versus time. The power spectral density of the displacements as a function of frequency, $P(f)$, is calculated from the discrete velocities. The RMS motion above a given f_0 is then obtained as the integral of $P(f)$ from f_0 to $315\,\mathrm{Hz}$. The measurements were taken over night, to have the quietest background conditions. Data were acquired with a sampling time of $0.001\,\mathrm{s}$ for about 3 minutes and the results were averaged over subsamples of $5\,\mathrm{s}$.

3 SIMPLE THEORY

Water induced vibrations are thought to be induced by the onset of turbulence in the water in the pipes. For a laminar motion, no vibrations should be generated since the water velocity at the internal wall of the pipe is zero. To estimate the water induced vibration the simplified approach of [7] and the results of [8] are referred to. The Reynold's number is defined as $Re = \frac{ud\rho}{\eta}$, where u is

* PhD student of the University of Lausanne, Institut de Physique des Hautes Energies (IPHE), Switzerland.

Table 1: Some parameter of the pipes at turbulent onset.

Pipe	Re	d [m]	Flow [l/h]	f_c [Hz]
Tap→Manifold	2000	0.013	16.4	10.5
Manif.→Quad	2000	0.008	40.3	27.9
Quadrupole	2000	0.003	15.1	198

the water velocity, d the pipe diameter, ρ=10^3 kg m^{-3} and η=$0.89\,10^{-3}$ kg m^{-1} s^{-1} the water density and dynamic viscosity. Turbulence occurs at around Re=2000, depending for instance on the roughness of the pipe surface, on the pipe shape and on the status of the water upstream of the pipe. The water motion will be assumed to be laminar upstream and downstream the pipe under consideration.

Turbulent motion is characterised by domains where the water has an eddy-like motion. These domains move with velocity u and have the typical size of order of magnitude of the pipe radius [8]. The lowest induced vibration frequency is expected to be of the order of $f_c = u/d$, which is a frequency associated to coherence domains of length equal to the tube radius. In Table 1 the values f_c at the turbulence onset are given for the different pipes of our experimental setup (see Fig. 1). The estimate of the minimal vibration frequency f_c gives the order of magnitude of the frequency window where turbulence effects are expected.

Here, the results from [7] are used to estimate turbulence induced quadrupole motion. The pressure drop along the pipe depends on u^2 as Δp=$\frac{\rho u^2}{2d} l\lambda$, where l is the pipe length and $\lambda \approx 0.316 Re^{-1/4}$=0.04 is obtained from empirical formulae [7]. Per quadrupole coil the value Δp=0.16 bar is found. Δp equals the average fraction of energy density converted to irretrievable turbulent kinetic energy, $\rho v^2/2$ (v is the instantaneous velocity). Assuming isotropy of turbulence and adding in quadrature the contributions of each coil and quadrupoles, the following expression is obtained for the RMS motion in the vertical y direction:

$$y^{\mathrm{RMS}} = \sqrt{n_{\mathrm{c}} n_{\mathrm{q}}} \frac{d}{2\pi} \frac{m_{\mathrm{water}}}{M_{\mathrm{Tot}}} \sqrt{\frac{\lambda}{6}},$$

where m_{water}=12.6 g is the pipe water mass, M_{Tot} the total mass of the object under investigation, n_{c}=4 and n_{q}=2 the coil and quadrupole number. In the pessimistic assumption that all the energy in concentrated around the f_c=393 Hz (at 30 l/h), for one isolated doublet the value $y^{\mathrm{RMS}} \approx 210$ nm is found. As the doublet is rigidly fixed on the table, it seems a better choice to define $M_{\mathrm{Tot}} \approx 700$ kg, which leads to $y^{\mathrm{RMS}} \approx 2$ nm.

4 RESULTS OF THE MEASUREMENTS

In Fig. 2 and 3 typical power spectral densities of vertical displacements of the doublet are given for different frequency ranges and water flows. Measurements were repeated on different days and showed a good reproducibility. The $P(f)$ peaks of the doublet with no circulating water

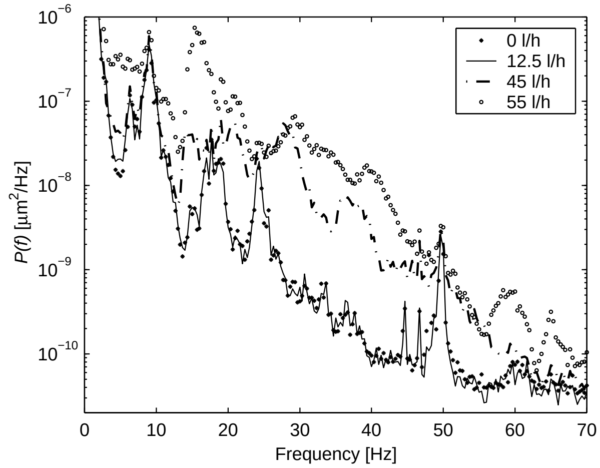

Figure 2: Power spectral density of vertical displacements vs.frequency as measured on top of the CTF2 doublet.

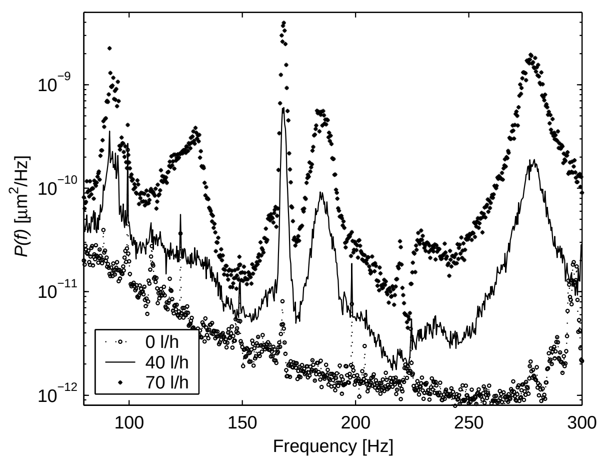

Figure 3: Power spectral density of vertical displacements vs.frequency as measured on top of the CTF2 doublet.

are mostly induced by floor motion, damped by a factor between 10 and 100 by the stabilising support [4]. In the vertical direction a new peak at around 9 Hz is induced by structural resonances of the quadrupoles.

The 12.5 l/h flow $P(f)$ of Fig. 2 is superimposed on the zero flow line. This reflects the threshold nature of the turbulence onset. Turbulence is found for flows above around 15 l/h only. The data of Table 1 suggest that the main source of turbulence in the few tens of Hz frequency range is the pipe from the tap to the manifold. The quadrupole pipes are expected to affect frequency $\gtrsim 200$ Hz. The pipes from the switch to the quadrupole can be important for flows above 40 l/h.

Above the turbulence threshold, two main effects induced by the circulating water are observed. (1) The released energy increases the overall noise level of the quadrupole vibrations. The existing peaks of $P(f)$ get considerably amplified. This is for instance the case of the peaks below 10 Hz and for the one at around 170 Hz (Fig. 2 and 3). (2) A number of new peaks arise, which are not

Table 2: Integrated RMS displacements above $4\,\mathrm{Hz}$, $20\,\mathrm{Hz}$ and $60\,\mathrm{Hz}$ on floor, on doublet rigidly clamped to a $700\,\mathrm{kg}$ table, for zero and operational water flow.

Vertical displacements			
f	Floor	Doublet 0 l/h	Doublet 30 l/h
4 Hz	3.62 nm	0.92 nm	1.30 nm
20 Hz	1.29 nm	0.21 nm	0.74 nm
60 Hz	0.07 nm	0.05 nm	0.06 nm
Horizontal displacements			
4 Hz	2.33 nm	0.35 nm	1.33 nm
20 Hz	0.43 nm	0.18 nm	0.80 nm
60 Hz	0.04 nm	0.04 nm	0.17 nm

present without turbulence. This is the case for a strong peak at $15\,\mathrm{Hz}$ (appearing above $45\,\mathrm{l/h}$) and for broad peaks in the 25-$45\,\mathrm{Hz}$ frequency range (see Fig. 2). In the higher frequency range these features are even more remarkable: amplifications of the zero flow vibration level of up to 1000 and more are clearly shown in Fig. 3. Three new peaks appear at $\approx 90\,\mathrm{Hz}$, $\approx 180\,\mathrm{Hz}$ and $\approx 270\,\mathrm{Hz}$, both in vertical and horizontal directions, whose amplitude increases for increasing water flows. However, the vibrations above $60\,\mathrm{Hz}$ contribute less than $0.2\,\mathrm{nm}$ to the total integrated motion (see below).

In Table, 2 some absolute values of the integrated RMS motion of the doublet are given for $4\,\mathrm{Hz}$, $20\,\mathrm{Hz}$ and $60\,\mathrm{Hz}$ and compared with the motion of the floor. For the CTF2 operational water flow of $30\,\mathrm{l/h}$, the vertical RMS motion above $4\,\mathrm{Hz}$ is $1.3\,\mathrm{nm}$, which meets the limit tolerance for CLIC [4]. Similar values are found for the horizontal displacement, where the tolerance is less demanding. The pure effect of the water is given by the difference in quadrature of the cases with and without flow. Above $4\,\mathrm{Hz}$ we obtain $0.9\,\mathrm{nm}$, which is comparable with the theoretical estimate assuming that the doublet and the table move as a whole. The water induced motion is strongly dependent on the water flow. In Fig. 4 we show vibrations versus water flow for different minimal frequencies. We find a maximum vibration level at around $60\,\mathrm{Hz}$. Interestingly, the vibration levels are lower at even higher water flows.

Vibration measurements of a doublet mounted on its CTF2-like alignment support, which was fixed on the stabilised table, have also been performed. The preliminary results show that the horizontal RMS motion above $4\,\mathrm{Hz}$ can be amplified by a factor of 2 and more. A support internal resonance at $37\,\mathrm{Hz}$ [4] is considerably amplified by turbulence and is the main contribution to the increased motion. The vertical direction is not much affected by the alignment support, as also confirmed by in-situ measurements of the CTF2 quadrupoles.

5 CONCLUSIONS

Preliminary results of water induced vibrations of a CTF2 quadrupole doublet have been discussed. Measurements have been done at constant pressure and in a wide range of water flows. Turbulence was found to be a threshold phenomenon that appears for water velocities in the quadrupole pipes above $0.6\,\mathrm{m\,s^{-1}}$ and induces an increase of the magnet vibrations. The main source of the low frequency vibrations (up to $60\,\mathrm{Hz}$) seems to be the turbulence onset in the pipes feeding the quadrupoles rather than in the quadrupoles themselves. They are the main source of the overall magnet RMS motion. Vibrations up to $60\,\mathrm{Hz}$ are also the typical range of magnet and support internal resonances, which can be considerably enhanced by the energy released in water turbulent motion. The simplified theory of [7] seems to give a good rough estimate of the frequency range of the turbulence induced vibrations and the order of magnitude of the RMS motion.

The effect of water flow in CLIC type quadrupoles has been quantified in detail. The results will feed into further design optimisation of the system (diameter of pipes, water velocity, support design,...). However, already the initial measurements have achieved the CLIC linac tolerances with nominal cooling water flow.

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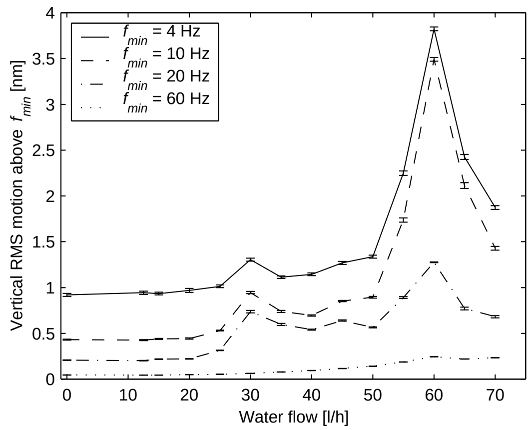

Figure 4: Vertical RMS motion above $4\,\mathrm{Hz}$, $10\,\mathrm{Hz}$, $20\,\mathrm{Hz}$ and $60\,\mathrm{Hz}$ vs. water flow.

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