HEAT COUPLING IN MULTI-WIRE VIBRATING WIRE MONITOR

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Abstract

Due to the extreme sensitivity of vibrating wire monitors (VWMs), it is possible to place these devices outside of an accelerator vacuum chamber in air to detect only very hard x-rays that penetrate the chamber. The VWM response time in air vs. vacuum is reduced substantially due to convective cooling. In this paper, the thermal coupling between the wires of a multi-wire VWM is described. Experiments in which x-ray sources were modeled by DC currents were performed to find the heat coupling coefficients between the wires. Using the assumption that the unknown beam transversal distribution is stable during the scan, a statistical data treatment allows the recovery of source profile from measured wire overheating.

INTRODUCTION

The operating principle of Vibrating Wire Monitors (VWM) is based on the measurement of the change in the natural frequency of a vibrating wire, which is stretched on a support, depending on the physical parameters of the wire and environment in which oscillations take place.

We have developed an electromechanical resonator with metallic vibrating wires excited by the interaction of a current with a permanent magnetic field. The interaction of the beam with the wire mainly causes heating of the wire and changes the frequency of natural oscillations. This value provides information about wire temperature and is a diagnostic of particles/photon intensity at the wire location.

The main characteristics of VWM are as follows:

- VWM is sensitive to thermal influence;
- thermal dependence is converted into purely mechanical response of the VWM, namely the change of the wire tension;
- the natural frequency of the wire depends exclusively on the mechanical parameters, (wire geometry and density, wire material elastic properties) and these characteristics remain stable during exposure to the beam of particles/photons in contrast with semiconductor characteristics (see e.g. [1, 2]);
- method of signal measurement is frequency, and not analog voltage or current;
- measurement currents produce much smaller thermal distortions in comparison with high-resistance thermometers.

VWM CHARACHTERISTICS

Because the operating principle of the VWM is based on the actual wire temperature dependence, it can be used in a very wide range of applications. At this time vibrating wire sensors have been applied to electron, proton and ion beams measurements (see [3, 4] and cited references). VWM can be used also for photon beam monitoring with a very wide spectral range from deep infrared up to hundreds of keV. First experiments were performed for hard X-ray monitoring in an accelerator at the APS ANL, both in vacuum and in air [5dipac1, 6dipac2, 7BIWGD].

Table 1: Main parameters of oscillators with wires using Stainless Steel and Tungsten.

Material, conditions	A316 Vacuum	A316 Air	Tungsten Vacuum	Tungsten Air
$\Delta T_{mean}/\Delta Q$, K/mW	19.4	0.23	3.0	0.23
$\Delta F/\Delta T_{mean}$, Hz/K at 4200 Hz	-40.2	-40.2	-8.8	-8.8
$\Delta F/\Delta Q$, Hz/mW	-779.6	-9.3	-26.4	-2.0
response time, s	20.2	0.26	1.8	0.15

Here ΔT_{mean} is wire mean overheating with power ΔQ deposited into the wire; ΔF is change of wire natural frequency

Technical characteristics of five-wire VWM using stainless steel with diameter 0.1 mm in air are as follows: resolution of frequency measurement of each wire is 0.01 Hz, short time accuracy measurement (1 hour) is ± 0.01 Hz and accuracy in 24-hour interval is ± 0.04 Hz, response time is 0.26 s. These values correspond to wire mean temperature resolution of 0.00025 K and short- and long-time temperature measurement accuracy of ± 0.00025 K and ± 0.001 K. With this device it is possible to measure power deposited on the wire at ± 1 μW for short time periods and ± 4 μW in long time mode. Nonlinearity of the pickup in operational range 0-100 mW is 0.01 %.

MULTIWIRE THERMAL COUPLING

If multiwire sensor is used in air, a thermal coupling between sensor wires occurs. In addition to external heat source (beam heating) on the wire, neighboring wires are also affected. In this case one must recover necessary information about the contribution of external source from the wire integral overheating.

In frame of linear heat transfer model the heat coupling between the wires can be determined from the following equations:

$$Q_1=\alpha_{11}T_1+\alpha_{12}(T_1-T_2)+\alpha_{13}(T_1-T_3)+\alpha_{14}(T_1-T_4)+\alpha_{15}(T_1-T_5),$$
$$Q_2=\alpha_{12}(T_2-T_1)+\alpha_{22}T_2+\alpha_{23}(T_2-T_3)+\alpha_{24}(T_2-T_4)+\alpha_{25}(T_2-T_5),$$
$$Q_3=\alpha_{13}(T_3-T_1)+\alpha_{23}(T_3-T_2)+\alpha_{33}T_3+\alpha_{34}(T_3-T_4)+\alpha_{35}(T_3-T_5),\quad(1)$$
$$Q_4=\alpha_{14}(T_4-T_1)+\alpha_{24}(T_4-T_2)+\alpha_{34}(T_4-T_3)+\alpha_{44}T_4+\alpha_{45}(T_4-T_5),$$
$$Q_5=\alpha_{15}(T_5-T_1)+\alpha_{25}(T_5-T_2)+\alpha_{35}(T_5-T_3)+\alpha_{45}(T_5-T_4)+\alpha_{55}T_5.$$

Here T_i are wires overheatings relative to the environmental temperature, Q_i is the power dissipated on the wire with index i. The right-hand parts of (1) define heat transfers with environment (diagonal terms) and with the other wires. Coefficients α_{ij} must be obtained by special experiments, however it is possible to determine them from beam scan data processing with the assumption that the unknown beam distribution is Gaussian..

The problem can be solved in a fashion similar to constant temperature anemometery (see e.g. [8]). With additional DC currents, frequencies can be stabilized at some level and in case of wire overheating by another source will be held at the same value by a corresponding decrease in DC current. The value of decrease is characteristic of the unknown source.

As an in-air application, five wires VWM with wire separation 0.5 mm were mounted on the outboard side of a bending-magnet synchrotron radiation terminating flange in sector 37 at the APS storage ring at distance of about 7 m from radiation source [7].

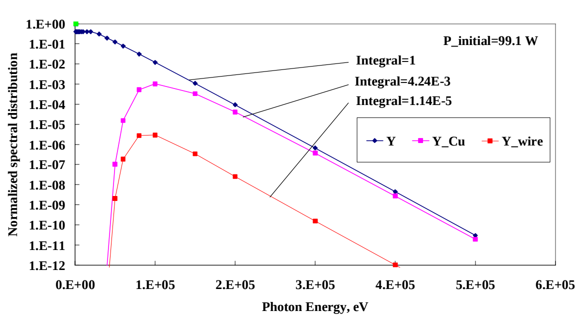

Fig. 1. Normalized spectral distribution of initial synchrotron radiation (Y), passing through the Cu flange (Y_Cu) and deposited into the wire (Y_wire).

Synchrotron radiation emitted in the horizontal angle corresponds to VWM005 aperture (about 8 mm) was 99.1 W (at 100 mA current). By use of spectral parameters for photon beam attenuation in Cu (material of flange) and Stainless Steel (material of wire) one can calculate the spectral distributions of synchrotron radiation transmitted through the flange and deposited into the wire (see Fig. 1). So synchrotron radiation power after 6 mm copper is 420 mW, while power dissipated into the wire is 1.13 mW. One can see from the list of VWM parameters that this value is sufficient for registration by this sensor. In Fig. 2 (left) we present the VWM overheating for five wires when electron beam was scanned vertically from minus 350 to minus 650 microradian angle using 125 steps. Profile asymmetries arise from above-mentioned wire thermal coupling and some inequality of placement relative to the sensor housing.

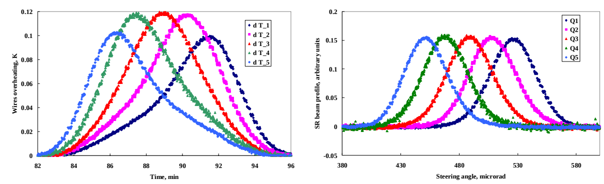

Fig. 2. Scan results presented by wire overheating temperatures (left) and recovered profiles from separate wires (right).

By data statistical treatment, heat coupling coefficients were found and using conversion equations (1) the source profiles were recovered (see Fig. 2(right)).

THERMAL COUPLING MODELLING

To investigate the wire thermal coupling in air we have provided some experiments with a five-wire sensor with the external source modelled by a DC current through the given wire. In Table 2 the wire overheatings in K are presented, where each row corresponds to the current of about 10 mA flowing through the adjacent wire. The wire separation was 0.5 mm (the second wire by technical reasons was omitted from measurements).

Table 2: Results of VWM thermal coupling study

wire 1	wire 2	wire 3	wire 4	wire 5
0.255	-	0.052	0.031	0.019
-	-	-	-	-
0.050	-	0.283	0.099	0.051
0.029	-	0.101	0.265	0.090
0.019	-	0.051	0.090	0.247

The values with good accuracy (about 0.001 K) are symmetric relative to both diagonals of matrix.

Another experiment with a five-wire VWM was performed to determine the thermal coupling dependence on the angle of the wires' plane to the horizontal plane. If the convection mechanism of thermocoupling is dominant then we expect a strong dependence on the angle. The 5-th wire of the VWM was driven with about 17 mA of DC current. The VWM was turned around its central wire with 30 degree steps. At each angular position at the 5-th wire the DC current was switched off and then switched on. Typical behavior of the one wire frequency is presented at Fig. 3. Here as an example we present the data for 3-rd wire when the wires' plane was horizontal.

For the first five and last five minutes of the experiment, the DC current through the 5-th wire was switched off.

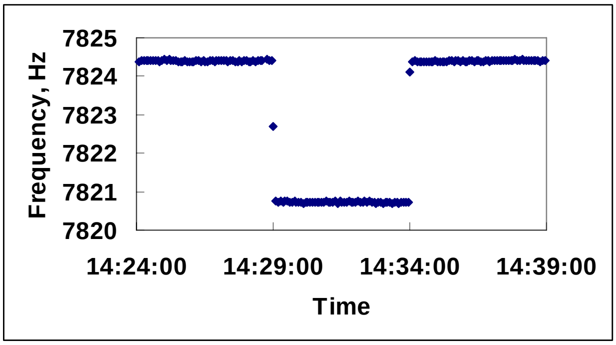

Fig. 3. Typical behavior of a wire frequency when the neighbor wire is heated.

In Table 3 the mean values of wires overheatings in K for all rotation angles is presented.

Table 3: Wire overheating range from device rotation

Wire N	1	2	3	4	5
Over-Heating, K	0.035	0.059	0.098	0.170	0.482

Dependence of wire overheating at each position is presented in Fig. 4. As the mean values of overheatings are different for all wires in Fig. 4 we present the difference between overheatings and their averages.

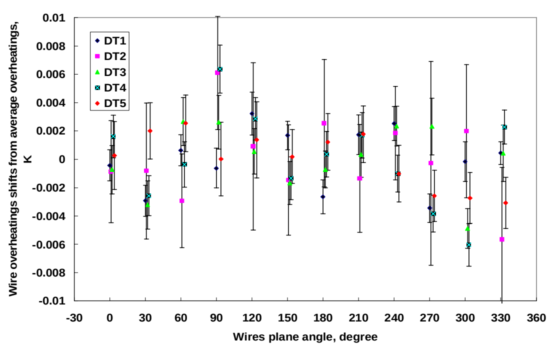

Fig. 4. Wire overheating dependence on the wires' plane rotation angle.

No significant dependence of the overheatings on angle here is seen. Perhaps the main mechanism of thermocoupling is direct thermoconductivity through the air (in vacuum thermocoupling is absent).

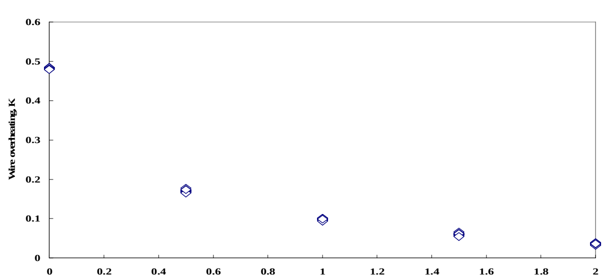

Fig. 5. Wire overheatings dependence on the distance from the heated wire (N 5).

In Fig. 5 we present the dependence of wires overheatings on their positions. This data must be used for proper theoretical application development.

DISCUSSION

Vibrating wire sensors can be used for many types of beam diagnostics because only a small amount of heat transfer from measured object to the wire is needed. Therefore vibrating wire sensors can be successively applied for electron, proton, ion and photon beam monitoring. In charged particle beam diagnostics it is possible to monitor the weak beams and to measure beam halo and tails. For photon beams it is possible to measure very hard spectral components. Because of this one can measure only necessary part of radiation from insertion devices and remove unwanted contributions from other softer radiation sources. A possible area of VWS application is in the area of neutral beam diagnostics.

The recent application of the VWS in air decreases the response time significantly and reduces VWS cost by a large factor. Use of multiwire sensors in air results in thermal coupling between wires, in addition to the direct heating from the beam under investigation. In this paper we show that with a statistical treatment and the assumption of a stable beam, the required profile of the beam can be recovered. It will be useful however, to develop a procedure to recover the beam profile without additional assumptions. For this purpose initial experiments of wire thermal coupling have been performed. Results require further theoretical explanation on the basis of a proper physical model.

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