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On the Featutrs of Double-Wire Vibrating Wire Monitor

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Abstract—The vibrating wire monitors are used for measuring transverse pro-files of radiation beams of different nature. For increasing the accuracy of scanning, and in some cases escaping the scanning procedure (measurement of the beam profile using a matrix of wires), it is proposed to use several vibrating wires. A monitor of this kind with two vibrating wires spaced apart at some distance formed the measuring unit of the laboratory stand, developed by us for training students in accelerator technology. The features of such a two-wire monitor and, in particular, the problem of laser radiation power redistribution between the wires are discussed.

Keywords: wire, vibrating, monitor, beam, test-bench

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1. INTRODUCTION

The wire scanners are used in many accelerators as a standard device for measuring the beam profile [1]. One can detect the signal from the beam—wire interaction in two different ways, either by detecting the scattered beam particles outside the vacuum chamber [2, 3], or by measuring the secondary electron emission current generated by particle beams [4, 5]. The monitors developed based on the second method represent a grid of wire electrodes [6, 7].

In 1999, with the view of diagnostics of particle accelerator beams it was proposed to use vibrating wires providing higher sensitivity [8] compared to wire scanners.

The use of vibrating wire monitors (VWM) for measuring the transverse profiles of various beams is based on the dependence of wire vibration frequency on its tension. With allowanc made for the increased temperature sensitivity of a wire pinched at both ends, such monitors proved to be sensitive to insignificant fluxes of particles/photons/neutrons, which raise the temperature of wire by magnitudes of the order and less than mK [9]. Beam profiling was performed by means of a beam scanning procedure. Owing to the low scanning speed determined by processes of wire thermalization, in case of changing of irradiation value the scanning usually takes several tens of seconds and in some cases is the main disadvantage of VWM.

To increase the accuracy of scanning, and in certain cases to promote the scanning process, it was proposed to use several vibrating wires. In [10], experiments were conducted with a two—wire monitor, and in [11]—with a five-wire monitor. Profiled in the first case was a beam of a semiconductor laser, and in the second one—a rigid part of synchrotron radiation passing through the copper flange of APS ANI accelerator. In both cases, a correlation of wire frequencies was observed, explained by the rescattering of heat fluxes between the wires. In case of measurement of the hard part of synchrotron radiation, there was also a contribution made by secondary particle fluxes formed at the scattering of heat fluxes by neighboring wires. A method for numerical estimation of the effects of scattering by wires was proposed in [12].

In the present work the research on this topic was furthered using a monitor with two vibrating wires that formed the measuring part of a laboratory stand devised within the framework of joint Armenian-German project of the Institute for CANDLE Synchrotron Research with the aim of training the students from Germany and Armenia in acceleration technology [13].

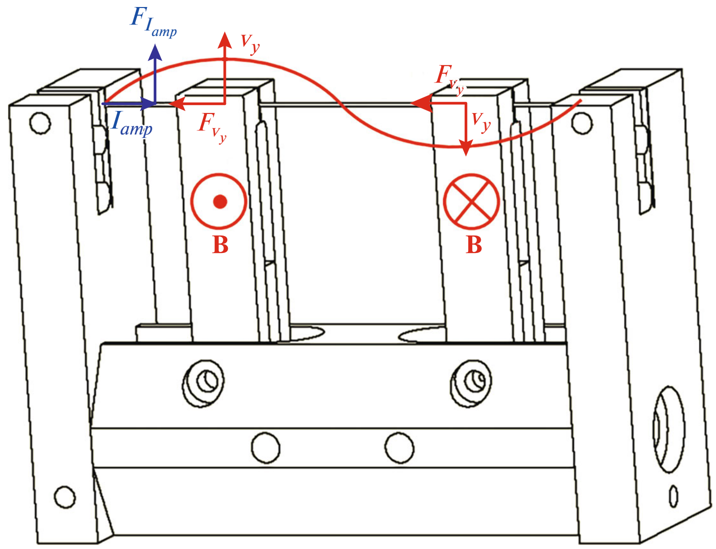

Fig. 1. The visualization of the process of generation of wave vibrations. **B**—magnetic poles, *F*—components of forces acting on the wire sections and electrons in the wire within the magnetic field, *v*—components of the velocity of the wire sections.

2. DOUBLE WIRE VIBRATING WIRE MONITOR

2.1. Features of a Two-Wire Vibrating Wire Monitor. The Temperature Dependence of the Frequency of Vibrating Wire

VWM is a wire pinched at both ends that is located in a magnetic field. The vibrations of a wire in the monitor are excited by the interaction of electric current passing through the wire with a constant magnetic field. Mechanical vibrations in the wire give rise to an electromotive force that is amplified and applied to the wire by means of a feedback circuit. This process causes an increase in random mechanical motion. Due to high Q-factor of the wire, vibrations remain near the resonance only at the natural frequency of wire (see for example [14]). The process of the generation of vibrations is shown in Fig. 1.

The use of two vibrating wires as a monitor is stipulated for by several reasons. It is larger by size than the beam and can be used as a beam positioning monitor. In this case, the monitor stays motionless. In the other version one can locate the wires at a close distance to serve as means for comparison of two identical beam scans with shifted measuring wires. However, in this case it is required to carefully separate the component of impact on the wire only from the beam being directly incident on the wire. Usually VWM are designed so that the beam be completely contained in the VWM aperture (the area between the magnetic poles and the VWM base) during the scanning. For VWM with two wires, the mutual influence of wires is observed. It can be heat transfer by means of convective (use of VWM in atmosphere) and radiative heat exchange

$$F = \frac{1}{L}\sqrt{\sigma/\rho}, \tag{1}$$

where F is the frequency, σ is the tension, L is the length of wire and ρ is the density of wire material. The initial tension of the wire is performed at temperature T_0 in the following manner: the loose wire with initial length L_0 is stretched and clamped to the base with L_A length between the pinching points (see Fig. 2a).

Schematically shown in Fig. 2c is the disposition of wires and the rescattering process: some part of the power incident on one of the wires is redistributed with K coefficient to the other.

The elongation of wire from L_0 to L_A means that there arises σ_o tension in it,

$$\sigma_0 = \frac{L_A - L_0}{L_0} E_W, \tag{2}$$

where E_W is the Young's modulus of the wire material. Let us suppose that as a result of exposure to the beam the initial temperature of the wire T_0 increases to T, assuming therewith that the temperature of the

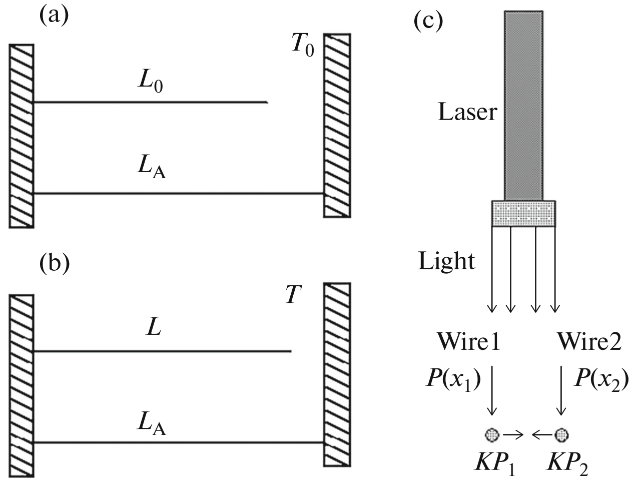

Fig. 2. The flux of laser radiation (vertical arrows) falls on both wires with different intensities: $P_1 = P(x_1)$ for the first wire and $P_2 = P(x_2)$ for the second ($P(x)$ is an arbitrary value normalized intensity distribution along the horizontal x-axis). Part of the radiation falling on one wire is redistributed to the second wire with the coefficient K (horizontal arrows).

base was not changed. The relative elongation of the loose wire depending on the temperature change $\Delta T = T - T_0$ is determined by the formula

$$\frac{L - L_0}{L_0} = \alpha_W \Delta T, \tag{3}$$

where α_W is the temperature coefficient of linear expansion of the wire material and L is the length of the loose wire as a result of a change in its temperature. In this case the tension of the wire σ is determined by the formula (see Fig. 2b)

$$\sigma = \frac{L_A - L}{L} E_W. \tag{4}$$

Assuming that the change in the length of wire in small in comparison with the initial one over all the range of temperatures of interest to us, one can put $L \approx L \approx L_A$ in the denominators of formulae (1)–(4), as well as taking into account that $\alpha_W \Delta T$ is much less than <1 in the entire range of temperatures under consideration, we obtain

$$\sigma = \sigma_0 - E_W \alpha_W \Delta T. \tag{5}$$

Here the frequency of wire will be written as follows:

$$F = \frac{1}{L_A} \sqrt{(\sigma_0 - E_W \alpha_W \Delta T)/\rho}. \tag{6}$$

It is convenient to rewrite formula (6) by expressing the dependence of the temperature change of the wire ΔT on the frequency:

$$\Delta T = \frac{\sigma_0}{E_W \alpha_W} \left(1 - \frac{F^2}{F_0^2} \right). \tag{7}$$

In the approximation of slow beam scanning with normalized to an arbitrary value particle distribution in $P(x)$ cross section, the change in wire temperature is proportional to the power that falls on the wire at the position x along the scanning axis and is transformed into heat (some part of power is carried away by scattered particle/radiation fluxes):

$$P(x) = a \Delta T(x). \tag{8}$$

where coefficient a depends on the properties of wire material, its preliminary tension, as well as the coefficient of transformation of the laser radiation incident on the wire into heat. The value of coefficient a is difficult to measure with proper accuracy, so the vibrating wire method usually reconstructs the beam pro-

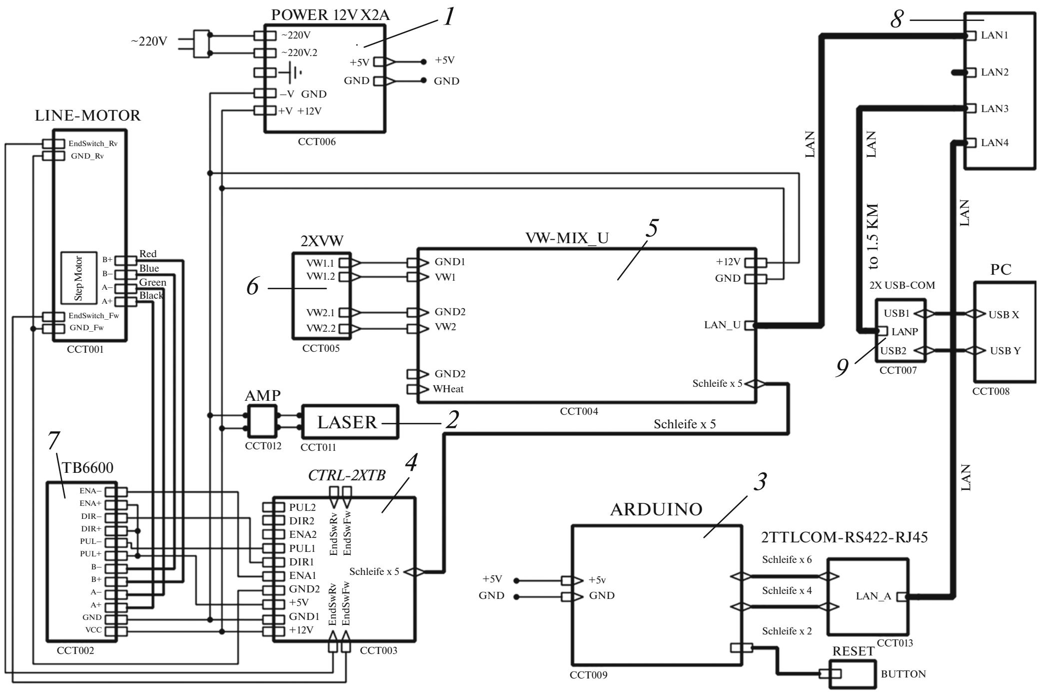

Fig. 3. The diagram of laboratory stand: *1*—power supply, *2*—laser, *3*—Arduino Mega 2560, *4*—the stepper motor control plate (CTRL-2XTB), *5*—the wire auto-generation plate (VW-MIX_U), *6*—VWM, *7*—the stepper motor-based linear actuator (TB6600), *8*—the network adapter, *9*—the Arduino interface to PC.

file in relative units. With allowance made for that, it is convenient to introduce the concept of a response from vibrating wire

$$S(x) = b(1 - F(x)^2/F_0^2), \tag{9}$$

where b is a normalization coefficient. It can be written taking into account the redistribution of scattered laser radiation between the wires (see Fig. 2c), that

$$S_1 = P_1 + KP_2, \quad S_2 = P_2 + KP_1, \tag{10}$$

where $S_1 = S(x_1)$, $S_2 = S(x_2)$, $P_1 = P(x_1)$, $P_2 = P(x_2)$ (hereinafter, the functions P and S are considered dimensionless, since formulas (8) and (9) contain undefined coefficients a and b; the coefficient K is defined in the caption to Fig. 2c). Solving equations (10) with respect to unknown quantities P_1 and P_2, we obtain:

$$P_1 = \frac{S_1 - KS_2}{1 - K^2}, \ P_2 = \frac{S_2 - KS_1}{1 - K^2}. \tag{11}$$

2.2. The Experimental Set-Up

The parameters of the two-wire monitor are: the material of the wires is the stainless steel (A316). The wires are 36 mm long, their diameter is 100 µm, the aperture—6 mm. The temperature dependence of the frequency of wire of ≈27 Hz/K ensures the temperature resolution of ≈0.4 mK (corresponds to the achieved in the experiment accuracy of frequency measurement of the order of 0.01 Hz for measurement intervals of the order of 1 s) and the resolution of the power incident on the wire of ≈80 NW. Shown in Fig. 3 is the laboratory stand containing all the components of the beam profiling system: the monitor with two vibrating wires and the stepper motor based linear actuator supply system (stepper motor) with the driver, the stepper motor control board and limiting switches, the interface with a computer, its inherent visualization system using an Arduino unit.

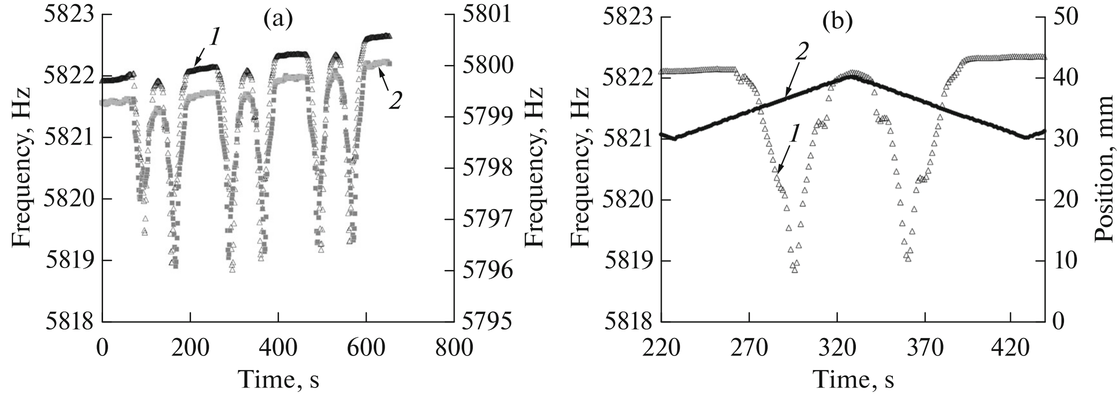

Fig. 4. The time dependence of wire vibration frequencies: (a) *1* and *2* are the frequency signals from both the wires. (b) The second scan: *1*—the frequency of the first wire, *2*—the position of VWM along the scanning axis.

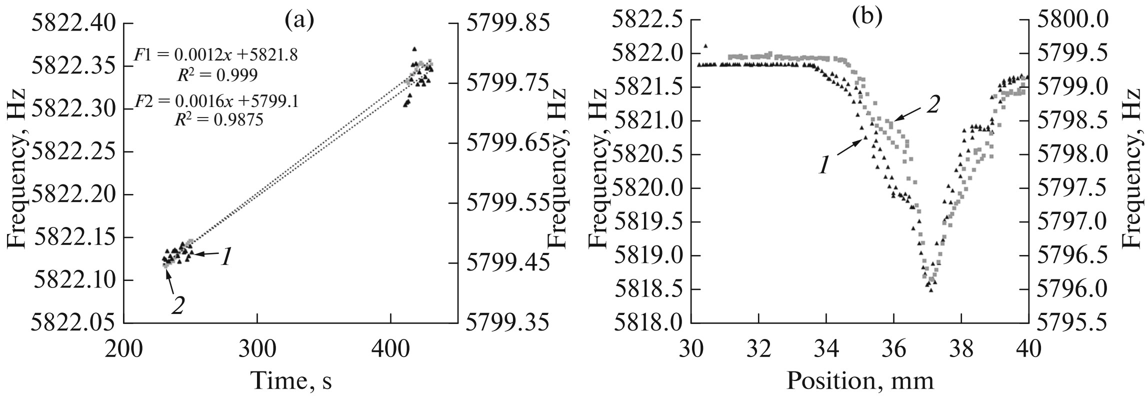

Fig. 5. (a) Calculations of drift parameters: *1* and *2*—frequencies of the first and second wires. (b) Frequency corrections for time drifts: *1* and *2*—frequency drifts of the first and second wires.

3. EXPERIMENTAL RESULTS AND THEIR PROCESSING

Figure 4a shows the results of the time dependence of the frequencies of both wires for three beam scans, consisting in the travel of the VWM by 10 mm from the initial position and turning back to the starting point (the scanning speed in this experiment being 0.1 mm/s) are shown. It can be seen from the figure that when the wires are not exposed to the laser beam, frequency drifts occur mainly due to changes in the ambient temperature. The upper segments of the curves correspond to the exit of the wires outside the laser beam during scanning. In Fig. 4b the second scanning of the beam (270–390 s) is highlighted for subsequent processing of experimental results, the frequency data from the first wire and the position of VWM along the scanning axis are presented.

The correction of frequency signals for thermal drift is performed as follows: the time intervals are isolated when the wires are not exposed to the beam, and a linear regression of frequencies is built according to these intervals (regression formulae are given in Fig. 5a).

The frequency graphs after corrections for the time drift are shown in Fig. 6b. Since the first and second wires are spaced relative to each other along the scanning axis, the coordinates for the values of frequencies from the second wire are also shifted by the value ≈ 0.93 mm, which provides the coincidence of the extremums of frequencies of both wires along the scanning axis. The graph of signals from both wires is shown in Fig. 6a, whence it is seen that these profiles do not coincide due to the effect of redistribution of laser radiation power between the wires and the use of algorithm (11) is required to correct the profiles. The calculation of coefficient K seems impossible due to the complex nature of the rescattering process, which depends on the relative position of the wires, the quality of their surfaces, and the corresponding radiation emission/absorption coefficients. To obtain K the fitting of experimental data was used. As a

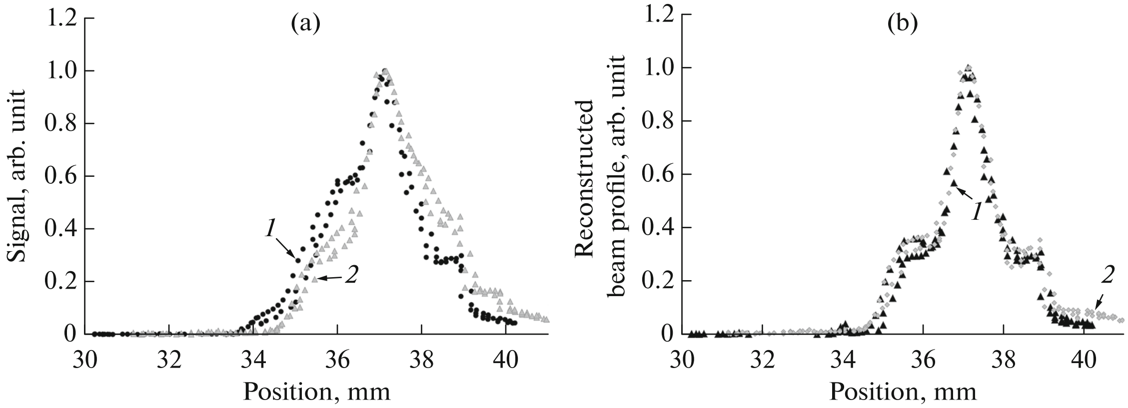

Fig. 6. Signals from both wires. (a) Coincidence of signals *1* and *2* from wires made by their maxima. (b) Reconstructed profile using signals *1* and *2* from wires.

result, a value of $K \approx 0.32$ was obtained. The beam profiles corrected for the rescattering process are shown in Fig. 6b.

4. CONCLSIONS

It should be mentioned that a formal model of a five-wire pickup proposed in [12] is based on the concept of wire heating temperatures. Then, a matrix representation of a unified measured profile is constructed (in [12] it is a beam of the rigid part of synchrotron radiation of the APS ANL storage ring). A large number of mutual thermal link coefficients between the wires were selected numerically without any relation to the physical model.

In the present paper as such a physical model we use the rescattering between the wires of the beam to be measured. The value of scattering coefficient is a function of many factors: the presence of an atmosphere, in case of laser radiation – the quality of wire surfaces and, the most importantly, the relative position of wires. It should be noted that the value of this coefficient obtained as a result of mathematical processing of primary data turned to be greater than those expected from tentative assessments. Apparently, for such coefficients the allowance for the multiple scattering of the radiation power should be made, as is done at calculations of the thermal problems containing a thermal radiation component [15, 16].

Besides, in case of beams with transverse dimensions of the order of VWM aperture (the area in which the wire is exposed to the measured beam), the wire frequencies are also affected by the scattered radiation of beam from parts of magnetic VWM system and the wire attachment points. It should be noted that the problems discussed in this paper testify to the sensitivity of frequencies to wire temperatures below and on the order of mK.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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