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PARTICLE AND PHOTON BEAM MEASUREMENTS BASED ON VIBRATING WIRE

S.G. Arutunian, G.S. Harutyunyan, E.G. Lazareva, A.V. Margaryan
Yerevan Physics Institute, 0036, Yerevan, Armenia
M. Chung, D. Kwak, Ulsan National Institute of Science and Technology, 44919, Ulsan, Korea

Abstract

The instrumentation introduced herein is based on high-quality vibrating wire resonator, in which the excitation of wire oscillation is made through the interaction of the wire current with a permanent magnetic field. The high sensitivity of the oscillation frequency to the wire temperature allows the resonator to be used for measuring charged-particle/X-ray/laser/neutron beam profiles with wide dynamic range. The beam flux falling on the wire increases its temperature from fractions of mK to hundreds of degrees. Another application method is to use the vibrating wire as a moving target, in which signals created at beam interaction with the wire are measured synchronously with the wire oscillation frequency. This method allows to effectively separate the background signals. Also, the well-defined (in space) and stable (in time) form of the wire oscillation allows the vibrating wire to be used directly as a miniature scanner for measuring thin beams. The latter two methods enable a significant reduction in scanning time compared to the original thermal-based method.

INTRODUCTION

Vibrating wire (VW) resonators have a number of attractive characteristics: high quality factor, long-term stability, practical absence of irreversible drifts caused by component aging. On the basis of such resonators, we have developed several instruments for measuring the profiles of beams of different nature (charged particles, electromagnetic radiation in a wide wavelength range, from infrared to hard gamma rays, neutrons). Three principles of operation of such instruments have been proposed. The first uses the dependence of the resonator frequency on the wire tension, which is determined by the flux of particles falling on the wire. The second one uses the signals of secondary particles in the interaction of the beam with the wire, and measurements are made synchronously with the string oscillations. In the third, the wire oscillations are used as a miniature scanner to scan beams in the micrometer size range.

THERMAL METHOD

The Vibrating Wire Monitor (VWM) on the thermal principle can be described as a wire stretched between two clips mounted on the basis. Part of the wire is placed in a magnetic field created by permanent magnets. The oscillations of the wire at natural frequency are excited by the interaction of the current flowing through the wire with the magnetic field. The wire is connected to the input of operational amplifier with positive feedback, which leads to autogeneration of natural oscillations of the wire (see [1] for details). The particles of the measured beam heat the wire, leading to a change in its tension and, accordingly, the frequency of oscillations, which serves as the output signal of the VWM. VWMs have good relative accuracy (several units per 1e-6), long-term stability (many months) and a large dynamic range (up to 6 orders of magnitude).

Let us describe the operation of the VWM using the example of a profiling station for the Cyclon18 proton accelerator with the particle energy of 18 MeV [2] (the results of studies will be published in more detail in [3]). Figure 1 shows the main units of such a station.

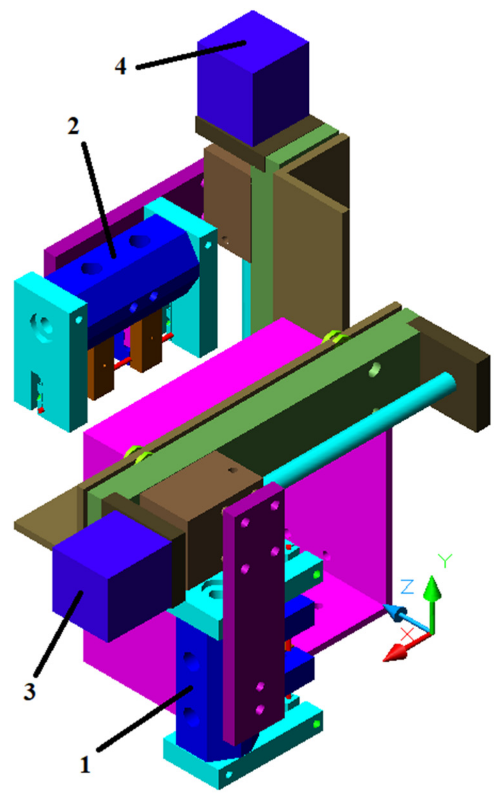

Figure 1: Profiling station for horizontal and vertical scanning, equipped with VWMs (1 and 2) and linear drive systems (3 and 4). Beam extends along the Z-axis.

Note that thermal monitors have response times ranging from fractions of a second to several seconds, depending on the wire material, the sensor geometry, and the atmosphere/vacuum in which the sensor is used. For the VWM used here (stainless steel string of length 56 mm, and 100 μm in diameter), this time is about 0.46 sec. The beam current was controlled by changing the current of the ion source located in the center of the cyclotron.

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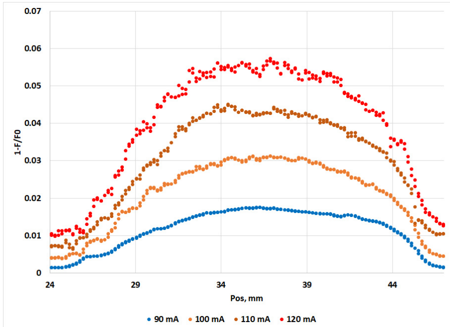

Figure 2: Vertical profiles of the proton beam for different values of ion source current (with scanning speed of 0.2 mm/s).

Figure 2 shows the results of vertical scans at ion source currents of 90 mA, 100 mA, 110 mA, and 120 mA.To estimate the beam current, we will use a formula that relates the relative frequency measurement to the current of particles exposed on the wire I_p [1]:

$$\frac{\Delta F}{F_0} = -\frac{E}{2\sigma_0}\frac{\alpha_W \varepsilon_{heat}(\delta_p I_p / e)}{\left[8\lambda S / L + 4\varepsilon\sigma_{ST\text{-}B} T_0^3 \pi dL + \alpha_{conv}\pi dL\right]}$$

where d, L, S, are wire diameter, length and cross-section; E, $\alpha_W, \lambda, \varepsilon$ are wire elasticity modulus, thermal expansion coefficient, thermal conductivity, and wire emissivity (set to 0.3); σ_0, F_0 are wire initial tension and corresponding frequency (second harmonic); α_{conv} is convection losses coefficient (set to 36 W/m^2/K), δ_p is proton ionization losses in wire (calculated by Bethe-Bloch formula and for d = 100 µm is about 1.3 MeV), ε_{heat} is coefficient of transfer ionization losses to heat (set to 0.3). Substituting the tabulated values for other parameters, we obtain that for an ion source current of 90 mA the total proton beam current is on the order of 1 µA (the corresponding distribution in Fig. 2 was fitted by a Gaussian function with an amplitude of 0.0175 and RMS distribution of 6.5 mm). Presented in Fig. 3 dependences of ion source current and proton current on maximum of obtained in Fig. 2 distributions allow to calibrate the proton beam current by values of ion source current.

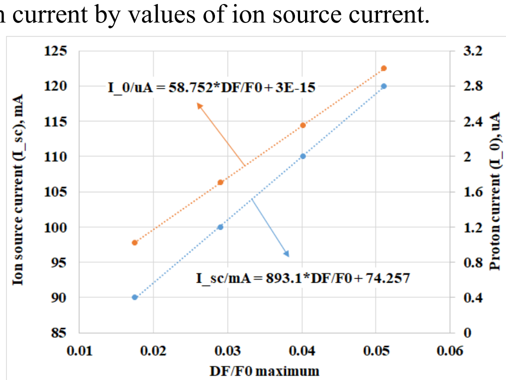

Figure 3: Dependences of ion source current and proton current on maximum distributions in Fig. 2.

VWM for Elastic Properties Investigation

VMWs can also be applied for measuring neutron fluxes penetrating the wire. It is proposed to use a vibrating wire exposed in the neutron flux, to observe the effect of neutron irradiation impact on the elastic properties of metals. The effect is caused by both neutron capture (mainly for neutrons with energy less than 1 MeV) and lattice disturbance during the atom-neutron collisions with energy more than 1 MeV. We suggest to use a two-wire monitor, in which wires are located in the same thermal space and are separated to significantly differentiate the exposure of neutrons to the wires. A prerequisite for a successful proposal is the long-term stability of VWM.

VW AS A RESONANCE TARGET

It is often necessary to produce a faster scanning of the beam. For this we proposed a hybrid method based on measurement of secondary particles during beam scattering on a wire (of traditional wire scanners), but using the vibrating wire as a target. Synchronous measurements with wire oscillations allow detecting only the signal generating from the scattering of the beam on the wire. This resonant method enables fast beam profiling in the presence of a high level of background. The concept was suggested in [4], and for photon beams it was realized in [5]. The method can be applied to different types of beams by simply choosing an appropriate detector for each case. For photon beams, fast photodiodes can be used, and for charged particles, scintillators combined with photomultipliers etc. (see Fig. 4).

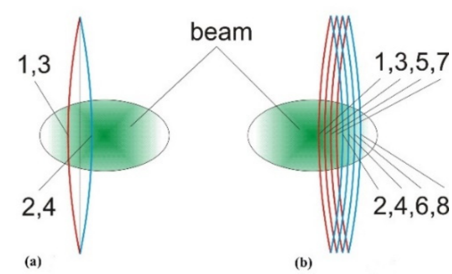

Figure 4: For odd indices the wire at its leftmost position, and for even indices the wire at its rightmost position: (a) the scanner is stationary; (b) the scanner is moving.

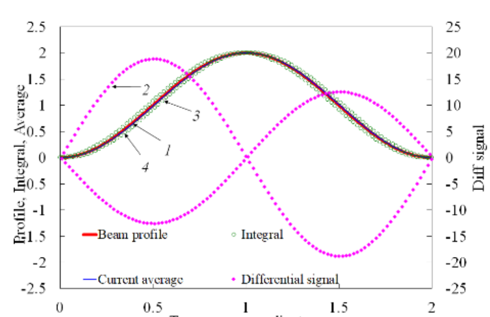

Figure 5: 1 - initial profile, 2 - differentiation of synchronized signal, 3 - integral of differential signal with sign inversing, 4 - current average of 3 practically recovers initial profile 1.

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For a certain data processing algorithm, the scanning speed can significantly exceed the speed of the wire during its oscillations [6]. The algorithm is as follows: a differential signal on the extreme positions of the vibrating wire is calculated, this signal is integrated (with inversion of the sign on the half-periods of wire oscillation) and then the current average procedure is applied to it. An example of using such an algorithm is shown in Fig. 5 - here the speed of scanning is 10 times higher than the average speed of the wire on one half-period of oscillations. The method was successfully tested in the laser beam tomography experiment [7].

VW AS A MINIATURE SCANNER

The idea of using the motion of a vibrating wire as a miniature scanner has been suggested in [5]. The amplitude of vibrations of the developed resonators of the vibrating wire reaches a few hundred micrometers. Such a range of wire motion is well suited for profiling micrometer-size beams. The first experimental results were obtained and a criterion of reliability of the results was determined in [8]. The experimental technique with laser beams has been further improved in [9, 10].

To implement the method, it is essential to have a strictly defined motion of the wire in space. In particular, it is desirable to exclude the mixing of harmonics of transverse vibrations in two orthogonal planes. For this purpose, in [10], a new magnetic field system with single poles providing the flatness of oscillations was developed.

It was also important to ensure fast measurement of secondary particles (for laser radiation these are photons reflected from the string surface). Fast photodiodes and fast operational amplifiers were used in [10]. The time of one measurement was about 10 μs, which required the development of an algorithm for processing the primary experimental data, taking into account the time derivative of the signal (calculated as the slope coefficient of the linear regression for seven current data points).

The motion of the wire center in all noted works was assumed to be sinusoidal. Under the conditions of the scheme of autogeneration of natural oscillations, i.e., periodic influence of the electronic circuit on the oscillation process, this statement required a proof. For this purpose, the following experiment was carried out in [10]: the oscillation feeding circuit was abruptly cut off and the observation of oscillations of the wire, which passed to the mode of free oscillations with damping, was continued. The measurements showed that the structure of the signals reflected from the wire did not change.

In addition, in [10], a technique for stitching profiles at displaced positions of the vibrating wire resonator was developed. The comparison of such profiles made it possible to determine the absolute parameters of the wire motion and to reconstruct the beam profiles in absolute coordinates. In the experiments, the profile of the focused beam of the semiconductor laser was measured, and the supply voltage was chosen so that inhomogeneities appeared in the beam profile. The results of the measurements are shown in Fig. 6.

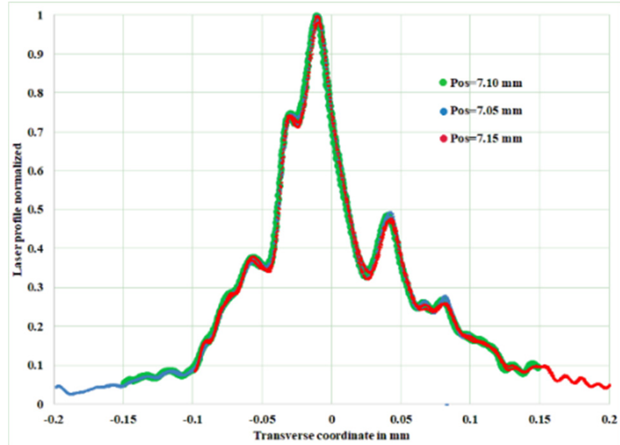

Figure 6: Reconstruction of the laser beam profile using the numerical differentiation of the primary photodiode signal.

Scanning of the profile in several positions of the vibrating wire monitor allowed us to restore the profile of the beam in absolute coordinates. The method of determining the laser beam profile by superimposing the overlapped profiles in several resonator positions of the vibrating wire is similar to the creation of a panoramic image by the stitching procedure. Image stitching is the process that combines images with overlapped areas to form an image with a wide view. Usually, after inputting a series of images with overlapped areas, feature matching is applied to find the corresponding points of the images for stitching, and then, translation is done to align them properly.

CONCLUSION

The beam diagnostic methods discussed above are united by the idea of using a vibrating wire as a sensitive element / resonant target / miniature scanner. Note that progress in one of these directions gives an opportunity to modify sensors for other methods of use. The unique properties of vibrating wire resonators allow one to search for more and more new possibilities for their use, such as studying the properties of neutron-irradiated wires.

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