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#### Abstract

A method for profile measurements of small transverse size beams by means of a vibrating wire is proposed. The main idea is to use the vibrating wire motion during its oscillations as a scanning mechanism and synchronously measure the scattered/reflected particles/photons created through the interactions of the measured beam with the wire. The method is expected to be applicable for thin beams in particle accelerators. The proof-of-principle test results, obtained using a laser beam, are presented.


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## INTRODUCTION

In accelerators worldwide, there are continuing efforts to achieve beams with smaller transverse sizes. Luminosity, a key figure of merit of colliders, directly depends on the transverse beam sizes at the interaction point; therefore, measuring and controlling small beam sizes ( $\ll 1 \mathrm{~mm}$ ) is crucial for collider experiments. ${ }^{1}$ In this regard, one of the main tasks in the design of the future colliders is to focus the beams at their interaction point in a spot of the order of several micrometers in diameter. ${ }^{2}$

By contrast, recent progress in the development of low emittance storage ring light sources based on the multibend achromat (MBA) concept (realized in MAX IV ${ }^{3}$ ) stimulates many synchrotron light source developers around the world to develop next generation synchrotron type radiation sources competing with freeelectron laser (FEL) designs. ${ }^{4,5}$ All of them need low emittance (low transverse size) beams.

Free-electron lasers (FELs) also require high brightness beams with small sizes. For example, for Swiss FEL, ${ }^{6}$ transverse beam sizes should be approximately $8 \mu \mathrm{~m}$.

New advanced particle accelerators should be operating with low emittance beams as well. For plasma-based accelerators, beam sizes should be in the submillimeter range (for example, see Refs. 7 and 8). The compact electron accelerator, whose structure is a dielectric microstructure excited by femtosecond laser pulses (dielectric laser accelerator), demands even submicrometric beam sizes. ${ }^{9}$

High quality electron bunches with small transverse beam sizes $(<100 \mu \mathrm{~m})$ are required for diffraction experiments, with a femtosecond time resolution. As an example of such facilities, we note the REGAE (Relativistic Electron Gun for Atomic Exploration) facility at DESY (Deutsches Elektrtonen-Synchrotron). ${ }^{1}$

Therefore, the measurement of beams with micrometer sizes becomes an important task in accelerator physics. In Ref. 12, the idea of using a wire movement during its oscillation for thin beam profile measurement was suggested. First, experimental results of a focused laser beam scanning were obtained in Ref. 13. The concept was based on the measurement of reflected photons of a laser beam from the wire. However, the photon measurement system used in Ref. 13 had a large time constant and needed a special mathematical method to correct the measurements.

In this study, we have developed a photon measurement system with a short time constant (about $10 \mu \mathrm{~s}$ ). This allows taking measurements faster and is more reliable. Furthermore, we applied precise positioning of the vibrating wire monitor (VWM) in the transverse direction. Two measurements from adjacent positions allow us to calibrate the sweep amplitude of the wire and recover the profile in absolute units. To snap the wire position in space during its oscillation, we used the sinusoidal electrical signal from the wire autogeneration feedback circuit, which was sharpened to have a well-defined triggering signal.

To demonstrate the proof-of-principle, the proposed method has been tested for the focused photon beam from a semiconductor laser.

## METHOD DESCRIPTION

During its oscillations, the wire vibrates at its first harmonic and sweeps a certain area in space. For beams with a transverse size of the order of the wire oscillation amplitude, the vibrating wire can be used as a scanner (see Fig. 1).

It is supposed that the wire oscillates in a plane, which can be adjusted relative to the beam axis for the convenience of reflected/scattered photon/particle measurements. Furthermore, it is supposed that the beam distribution in the vicinity of the vibrating wire does not depend on the longitudinal coordinate $y$. The scale of Fig. 1 is chosen for clear visualization of the proposed measuring scheme and does not correspond to the real size of the system. In reality, the transverse beam sizes and the scan area are the size of the wire oscillation amplitude (i.e., a few wire diameters) and much less


FIG. 1. (a) The beam (1) is intercepted by the oscillating wire. The $x$-axis is directed along the wire at its central position, the y -axis is directed along the beam propagation, and the $z$-axis is directed along the beam transverse direction. The positions of the wire at different times during its oscillation are denoted by (2) and (3). (b) The plane of the wire oscillations (2) is rotated by $30^{\circ}$ relative to the beam axis (1). The scale of the figures does not correspond to the real sizes.
than the wire length. Therefore, we assume that the wire intercepts the beam volume as a straight line. We denote the projection of the beam distribution on the $z$-axis as $P(z)$.

The number of photons/particles generated from the interactions of the beam with the wire (reflected photons for a visual range laser, secondary particles/photons for a beam of high energy particles or hard electromagnetic radiation) is proportional to the beam density profile $P(z)$ at the wire position $z$. The profile obtained by the photons/particles accepted by the measurement system is denoted as follows:

$$
\begin{equation*}
P_{H}(z)=k P(z) . \tag{1}
\end{equation*}
$$

Strictly speaking, the proportionality factor $k$ depends on the coordinate $z$, but if the measurement geometry does not change effectively during the photon measurements, we can neglect this dependence. For the vibrating wire, it means that the distance to the photon measuring system is much larger than the wire oscillation amplitude.

## EXPERIMENTS WITH A LASER BEAM

## Main setup

The proposed method was tested experimentally using a laser beam. We used a semiconductor laser with beam sizes of approximately 2 mm . The beam was focused by optical lenses with focal lengths of approximately 10 mm . The vibrating wire monitor (VWM) was mounted on the table with a precise manual feed. A photodiode was mounted on the vibrating wire monitor as well. We used two electronic boards: one for oscillation generation and the other for photodiode measurement. The aim of the experiment was to measure the transverse profile of the focused laser beam. The main setup of the experiment is presented in Fig. 2.

Here, we present a short description of the components of the experiment.


FIG. 2. Layout of the experiment: 1-semiconductor laser, 2-laser beam focused at the wire intercept position, 3-vibrating wire of the VWM, 4-photons reflected from the wire, 5-photodiode, 6-wire oscillation excitation electronic board, 7four channel measuring system (channel 1 for data from the photodiode and channel 2 for the triggering signal from the wire), 8-PC for data acquisitions, and 9—precise positioning system for the VWM.

To provide a large area swept by the wire oscillations, we used a VWM with the following resonator parameters: a $100 \mu \mathrm{~m}$ diameter wire made from stainless steel, a wire length of 80 mm , a magnetic field adjusted for first harmonic generation, and a VWM aperture of approximately 40 mm . The wire oscillations are generated by the interaction of an AC current through the wire with a permanent magnetic field. ${ }^{14}$ A feedback circuit selects the resonant frequency at which the AC current frequency is equal to the wire's natural frequency. As a result, a sine-type output signal is produced. This signal is sharpened to a rectangular form and used as a triggering signal for the photodiode measurements.

A semiconductor laser (Laser Pointer JD-850) with a wavelength of 532 nm and a power of 100 mW was used. The focusing system consisted of two optical lenses with focal lengths of approximately 10 mm .

A high speed and high sensitivity silicone PIN VBPW34S photodiode was used for photon detection (the radiant sensitive area is $7.5 \mathrm{~mm}^{2}$, and the rise time of 100 ns corresponds to a 43 ns photodiode time constant).

The VWM resonator was mounted on the table with a manual micrometer positioning system of $10 \mu \mathrm{~m}$ feed resolution. On the VWM resonator, an adjustable arm was mounted to allow the photodiode to collect the back scattered photons. The plane of oscillations had a slope of approximately $45^{\circ}$ relative to the beam direction.

The photodiode measurement system is based on an ATTINY2313 microcontroller. The system has four separated channels for four analog measurements in the range of 130 mV . Each channel contains an operational amplifier and a 12 bit analog to digital converter (ADC). The measurement cycles for all channels are simultaneously initialized by the vibrating wire frequency triggering signal. The measurements with the clock frequency follow after a few microsecond chip-select disable time. Each ADC measurement is accomplished with parallel writing into a memory chip accessed via a simple Serial Peripheral Interface. The procedure allows us to write approximately 8000 experimental points in 2 byte format for each channel. Each experimental data package forms an array of the sequential measurements of photons and electrical signals from the wire. The analog part of the photodiode measurement system was modified compared to the system described in Ref. 13 (by using a more optimal arrangement of components). Measurements of the photodiode and triggering signals were taken using two channels of the board.

## Dynamic behavior of the measurement system

In Ref. 13, a problem of dynamic response of the measurement system was noticed. It was pointed out that the measurement system exhibited a first-order behavior, which can be treated by the following equation: ${ }^{15,16}$

$$
\begin{equation*}
\tau \frac{d g(t)}{d t}+g(t)=f(t) \tag{2}
\end{equation*}
$$

where $f(t)$ is the input signal (real value of the physical process), $g(t)$ is the output of the measurement system, and $\tau$ is the time constant of the system. In Ref. 13, attempts to estimate the measurement system's time constants were made and a special algorithm for recovering input signals from the measurement data (output signal) based
on the knowledge of this parameter was developed. In this paper, we provide a more accurate way of measuring the time constant.

To obtain the parameter $\tau$, the following step-type input is usually implemented: $f(t)=0$ for $t<0$ and $f(t)=f_{0}=$ const. for $t \geq 0$. In this case, the output signal exponentially approaches the value $f_{0}$ through the function $g(t)=f_{0}(1-\exp (-t / \tau))$. By fitting the measurement data with this exponential type function, the parameter $\tau$ can be deduced. In our case, the input function $f(t)$ is the laser radiation created by the laser semiconductor pumping system powered by a separate power supply. Even at the step functionlike powering of the laser, we have not reached a step-type laser radiation at the exit. To overcome this issue, we suggest using input pulses symmetrical in time. For this, we developed a simple mechanical unit that consists of a rotating disk with a few holes around the circle. Continuous laser radiation cut by the disk becomes completely symmetrical laser pulses. Clearly, the measurement system with a small time constant maintains the symmetry, whereas for a large time constant, the symmetry is completely distorted.

The results of direct measurements for the large time constant electronics and upgraded electronics are presented in Fig. 3 (hereafter, as a unit of time, we use one measurement period equal to $12.45 \mu \mathrm{~s}$ ). As one can see for the upgraded electronics, the shuttered laser radiation pulses at a frequency of 1160 Hz produce practically symmetrical output signals. On the contrary, even after decreasing the shuttering frequency by more than half (frequency is 427 Hz ), the shape of output measurements remains strongly asymmetric.

The assumption that the input signal is symmetrical allows us to obtain the time constant of the measurement system. The process of estimating the time constant of the measurement system with slow electronics is illustrated in Fig. 4. Blue dots denote the experimental data, and the orange dots represent the mirror image of the


FIG. 3. Horizontal axis (bottom and top): time step with one unit corresponding to $12.45 \mu \mathrm{~s}$. Blue points-signals from the disk rotating with a frequency of 1159.9 Hz measured by upgraded electronics (one period of the input signal consists of 69.25 steps; the shape of signals is symmetrical). Orange points-signals in the same time range from the disk rotating with a frequency of 427.254 Hz measured by electronics with a large time constant ${ }^{13}$ (one period of the input signal consists of 188 steps; the shape of signals is asymmetric at lower frequencies).


FIG. 4. Horizontal axis: time step with one unit corresponding to $12.45 \mu \mathrm{~s}$. Estimation of the time constant of the measuring system with slow electronics (used in Ref. 13) ( $\tau=$ 19.5 and shift = 54).
experimental data (i.e., reflections of the time coordinates of the data with respect to the center of the measuring time range). Using Eq. (2), we recover the input signal with the following numerical algorithm:

$$
\begin{equation*}
f_{i}=\tau\left(g_{i}-g_{i-1}\right)+g_{i} . \tag{3}
\end{equation*}
$$

We apply the same procedure for the mirror pulse, $f_{i}^{\text {reflect }}$. Moving $f_{i}$ and $f_{i}^{\text {reflect }}$ toward each other by the step shift, we look for shift and $\tau$ which yield the best overlap of $f_{i}$ and $f_{i}^{\text {reflect }}$. By minimizing the root mean square of the difference between $f_{i}$ and $f_{i}^{\text {reflect }}$, we find $\tau=19.5$ and shift $=54$.

We prepared the same procedure for fast electronics. Figure 5(a) shows the output signal with its adjusted mirror signal at the same time. Overlapping of the two curves is good except for small deviations at the areas of entry and exit from the laser pulse. A small correction at the level of $\tau=1.1$ corrects this behavior [see Fig. 5(b)]. Comparing the results presented in Figs. 4 and 5, one can see essential enhancement of the measuring system (parameter $\tau$ decreases from 19.5 to 1.1).

In the following experiments, we used only the upgraded measurement system and neglected the presence of the small time constant of approximately 1 measuring step ( $12.45 \mu \mathrm{~s}$ ).

## Wire position snap in space

The second important step is to define the position of the wire in space at any given time. The wire's transverse coordinates during its oscillation are described by the following formula:

$$
\begin{equation*}
z_{i}=A \cos \left(2 \pi F t_{i}+\varphi_{0}\right)+z_{\text {pos }}, \tag{4}
\end{equation*}
$$

where $A$ is the amplitude of the wire oscillation projected on the $z$ axis, $F$ is the oscillation frequency, $z_{\text {pos }}$ is the VWM position along the transverse axis, and $\varphi_{0}$ is the phase constant. The parameter $z_{p o s}$ can be changed manually by the movement of the VWM with a precise mechanical feed system.

Thereby, the wire's subsequent coordinates $z_{i}$ are calculated according to the following formula:

$$
\begin{equation*}
z_{i}=A \cos \left(2 \pi\left(i-i_{*}\right) /\left(i_{* *}-i_{*}\right)+\varphi_{0}\right)+z_{p o s}, \tag{5}
\end{equation*}
$$



FIG. 5. Horizontal axis: time step with one unit corresponding to $12.45 \mu \mathrm{~s}$ : (a) $\tau=0$ and shift $=0.2$; (b) $\tau=1.1$ and shift $=1.3$.


FIG. 6. (a) Horizontal axis: time step with one unit corresponding to $12.45 \mu \mathrm{~s}$. Experimental data for the VWM position at $z_{\text {pos }}=0 \mathrm{~mm}$. Blue dots-photon counts, red dots-triggering signal (coming from the oscillation autogeneration feedback circuit). One can see that the maximal counts of photons practically coincide with the rising edge of triggering signals. (b) Photon count dependence on the transverse coordinate ( $\varphi_{0}=0$ ).
where $i_{*}$ and $i_{* *}$ are subsequently measured time steps within the triggering signal's rising edge ( $i_{*}<i<i_{* *}$ ). At every period of the wire oscillations detected by the triggering signal, the indices $i_{*}$ and $i_{* *}$ are changed. The applied algorithm allows taking into account slow drifts of the frequency arising from, for example, wire heating by the laser beam.

To obtain the parameter $\varphi_{0}$, we can use the triggering signal from the wire. However, there is no direct coupling between phases of electrical signals and the position of the wire in space. To solve this problem, we tried to use a laser beam measurement outside the core area. Experimentally, this situation was realized for the position $z_{p o s}=0$ (at this position, the center of the laser beam is not placed into the wire's oscillation sweep).

In Fig. 6(a), experimental ("raw") data of two channels are presented, namely, the photodiode output and the triggering signal from the wire oscillation excitation board. Data presented in Fig. 6(a) show that the positions of the maximal number of measured photons are practically matched with the rising edge of the triggering signal. Therefore, these edges can be used as a reference for estimating the vibrating wire's position along the transverse $z$ axis during oscillations. In addition, one can see that the periodicity of the photodiode measurements coincides with the triggering signal from the wire. Thus, the center of the measured beam is not placed in the wire oscillation sweeping area.

By substituting values $z_{i}$ of Eq. (5) into the experimental data of photon counts $P_{H}\left(z_{i}\right)$ corresponding to Fig. 6(a) with $\varphi_{0}=0$, we obtain the photon profile as presented in Fig. 6(b) (the z-coordinate is measured in units of oscillation amplitude $A$ relative to the VWM position).

All the data correspond to 400 measurements (approximately 6.5 periods of wire oscillations with a total time of 5 ms ).

After the shift of the VWM by -0.04 mm , the sweep area of the vibrating wire captures the center of the laser beam. Figure 7(a) shows the raw experimental data for the VWM position $z_{\text {pos }}=-0.04 \mathrm{~mm}$.

One can see sufficient broadening of the photon count dependence on the transverse coordinate [see Fig. 7(b)].

Another measurement cycle was done for the VWM position $z_{\text {pos }}=-0.11 \mathrm{~mm}$ (see Fig. 8).

The apparent profile line broadenings at both VWM positions are caused by the following effects: inaccurate parametrization of the wire oscillation coordinates when setting the parameter $\varphi_{0}=0$, laser power instability (noticed in Ref. 13), small but non-negligible measuring system's time constant, and possibly nonflatness of the wire oscillations. Corresponding data processing including deviations of $\varphi_{0}$ and the nonzero time constant of the system $\tau$ is discussed in the following section.

## Data processing and absolute calibration of the beam profile

In this section, we try to take into account the nonzero time constant $\tau$ of the measuring system and variation of the phase shift $\varphi_{0}$ when recovering the wire position $z_{i}$ in time steps. Data processing is prepared separately for each period of measurement data. For the array of $z_{i}$, we use Eq. (5) with $z_{\text {pos }}=0$, so values $z_{i}$ here describe the shifts of the wire center relative to the VWM position. According to Eqs. (2) and (3) with the "raw" data of photon counts, we recover



FIG. 7. (a) Horizontal axis: time step with one unit corresponding to $12.45 \mu \mathrm{~s}$. At the VWM position $z_{p o s}=-0.04 \mathrm{~mm}$, the sweep area of the vibrating wire captures the laser beam center: blue dotsphoton counts, red dots-triggering signals. (b) Photon count dependence on the transverse coordinate ( $\varphi_{0}=0$ ).


FIG. 8. (a) Horizontal axis: time step with one unit corresponding to $12.45 \mu \mathrm{~s}$. At the VWM position $Z_{p o s}=-0.11 \mathrm{~mm}$, the sweep area of the vibrating wire captures the laser beam center: blue dotsphoton counts, red dots-triggering signals. (b) Photon count dependence on the transverse coordinate ( $\varphi_{0}=0$ ).
the input signal $P_{R E C}\left(z_{i}\right)$ by the formula

$$
\begin{equation*}
P_{R E C}\left(z_{i-1}\right)=\tau\left(P_{H}\left(z_{i}\right)-P_{H}\left(z_{i-1}\right)\right)+P_{H}\left(z_{i}\right), \tag{6}
\end{equation*}
$$

where $2 \leq i \leq\left(i_{* *}-i_{*}+2\right)$.
To avoid problems of laser beam power variation, it is convenient to normalize the photon counts by the maximal value of the array $P_{\text {REC_MAX }}$ for the chosen period of wire oscillations,

$$
\begin{equation*}
P_{\text {NORM }}\left(z_{i}\right)=P_{\text {REC }}\left(z_{i}\right) / P_{\text {REC_MAX }} \tag{7}
\end{equation*}
$$

for $1 \leq i \leq\left(i_{* *}-i_{*}+1\right)$.
To determine the fitting parameters $\tau$ and $\varphi_{0}$, we use the following procedures.

The range $(-1,1)$ of variation of the coordinate $z_{i}$ was divided into 9 partially overlapped subranges: $(-1,-0.6),(-0.8,-0.4)$, $(-0.6,-0.2),(-0.4,0),(-0.2,0.2),(0,0.4),(0.2,0.6),(0.4,0.8)$, and $(0.6,1)$. In each subrange, we applied a second order polynomial regression, i.e., the relationship between the variable $z_{i}$ and the dependent variable $P_{\text {NORM }}\left(z_{i}\right)$ is modeled as a second order polynomial,

$$
\begin{equation*}
P_{F I T}\left(z_{i}(j)\right)=a(j) z_{i}^{2}(j)+b(j) z_{i}(j)+c(j) \tag{8}
\end{equation*}
$$

where the index $j$ denotes the subrange number, array $z_{i}(j)$ is the set of all coordinates $z_{i}$ belonging to this subrange, and $a(j), b(j), c(j)$ are coefficients of second order regression obtained by the well-known least square algorithm. Application of this regression allows us to assign for each period a value of experimental data noise Err by the formula

$$
\begin{equation*}
E r r=\sum_{j=1}^{9} \operatorname{SSE}(j) / n(j) / 9 \tag{9}
\end{equation*}
$$

where $n(j)$ is the number of experimental points belonging to the subrange $j, \operatorname{SSE}(j)=\sum_{i=1}^{n(j)}\left(P_{\text {NORM }}(i, j)-\left(a(j) z_{i}^{2}(j)+b(j) z_{i}(j)+\right.\right.$ $c(j)))^{2}$ is the sum of the corresponding squared errors. Here, $P_{\text {NORM }}(i, j)$ is the array of experimental points belonging to the subrange $j$.

An example of the fitting procedure for the VWM position $-0.04 \mathrm{~mm}, i_{*}=794$, and $i_{* *}=855$ is presented in Fig. 9 .

The regression procedure was done for five periods for the case of VWM position -0.04 mm . Ranges were chosen to minimize the number of outliers in the experimental data, taking into account a strong sensitivity to outliers for the second order polynomial
regression. The results of the regression are summarized in Table I where indices of time steps for five periods are presented in the first row.

The same processing was done for the case of VWM position -0.11 mm for five subsequent periods (see Table II).

By comparing values in Tables I and II, one can see good reproducibility for fitting parameters. The corresponding normalized profiles for VWM positions -0.04 mm and -0.11 mm are presented in Fig. 11. Transverse coordinates are adjusted relative to the VWM positions so that the range of transverse coordinates in both cases is $(-1,1)$.

The profiles presented in Fig. 10 are the observation of the same laser beam profile in two different positions of the VWM and should be overlapped in a unified coordinate system. The best overlap of these two plots is achieved at shift $=1.012$ in units of wire oscillation amplitude (see Fig. 11). Fitting was done in the same


FIG. 9. Experimental data of one period scan for the VWM position -0.04 mm have been transformed according to Eq. (6) with $\tau=1.1$ and normalized to the maximum value in the range. The coordinates are calculated according to Eq. (5) with $\varphi_{0}=0.034$ [to arrange the transverse coordinate in the range $(-1,1)$, we formally set $z_{p o s}=0$ ]. For better visualization of the data in subranges and further regression, the corresponding points are presented with markers of different colors and sizes. Dashed curves present the second order polynomial regressions for the corresponding subranges.

TABLE I. Regression procedure for the VWM position of -0.04 mm .

|  | $794-855$ | $855-917$ | $917-978$ | $978-1038$ | $1038-1099$ | Average |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: |
| $E r r$ | $5.922 \times 10^{-04}$ | $3.331 \times 10^{-04}$ | $2.107 \times 10^{-04}$ | $2.696 \times 10^{-04}$ | $2.144 \times 10^{-04}$ | $3.24 \times 10^{-04}$ |
| $\tau$ | $1.100 \times 10^{+00}$ | $9.000 \times 10^{-01}$ | $9.000 \times 10^{-01}$ | $1.200 \times 10^{+00}$ | $1.100 \times 10^{+00}$ | $1.04 \times 10^{+00}$ |
| $\varphi_{0}$ | $3.400 \times 10^{-02}$ | $5.200 \times 10^{-02}$ | $7.400 \times 10^{-02}$ | $7.000 \times 10^{-02}$ | $5.000 \times 10^{-02}$ | $5.60 \times 10^{-02}$ |

TABLE II. Regression procedure for the VWM position of -0.11 mm .

|  | $123-185$ | $185-246$ | $246-306$ | $306-367$ | $367-429$ | Average |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: |
| Err | $3.317 \times 10^{-04}$ | $2.807 \times 10^{-04}$ | $3.983 \times 10^{-4}$ | $3.203 \times 10^{-04}$ | $2.931 \times 10^{-04}$ | $3.25 \times 10^{-04}$ |
| $\tau$ | $1.100 \times 10^{+00}$ | $1.400 \times 10^{+00}$ | $8.000 \times 10^{-01}$ | $1.000 \times 10^{+00}$ | $1.100 \times 10^{+00}$ | $1.08 \times 10^{+00}$ |
| $\varphi_{0}$ | $5.200 \times 10^{-02}$ | $9.000 \times 10^{-02}$ | $9.400 \times 10^{-02}$ | $2.200 \times 10^{-02}$ | $4.600 \times 10^{-02}$ | $6.08 \times 10^{-02}$ |

manner as for the choice of proper parameters $\tau$ and $\varphi_{0}$ [regression procedure for the parameter shift was made in the overlapping interval $(-1+s h i f t, 1)]$. Fitting error for the data in the overlapping interval is estimated to be $1.127 \times 10^{-03}$ which is about three times larger than the corresponding error for measurement at one VWM position. Nevertheless, this indicates a fairly good agreement of the profiles measured at two different monitor positions.

This overlapping procedure enables us to obtain the scaling factor. The 1.012 units of oscillation amplitude (i.e., the amount of the necessary shift) correspond to 0.07 mm measured by precise mechanical positioning of the VWM. Applying this scaling factor


FIG. 10. Left peak corresponds to the VWM position -0.11 mm and the right peak to -0.04 mm . For both cases, transverse coordinates are estimated relative to the corresponding VWM positions ( -0.04 mm and -0.11 mm ) in units of wire oscillation amplitude. The nonuniform filling of points along the $z$ coordinate is caused by the nonlinear movement of the wire in space: more measurements are eventually accumulated at the points corresponding to the maximum displacement of the wire from the equilibrium position.
for the data of Fig. 11, we recover the laser beam profile in absolute units (see Fig. 12).

The scaling factor also allows us to find the vibrating wire oscillation amplitude, i.e., $\mathrm{A}=69 \mu \mathrm{~m}$. Also from Fig. 12, we find the size of the beam (full width at half maximum is $35 \mu \mathrm{~m}$ ). This value is matched quite well with the rough estimation by means of a special calibration ruler with a grid size of $30 \mu \mathrm{~m}$. The spot of the laser beam occupied about 1-1.5 cells of the grid. In principle, the amplitude of wire oscillation defines the limit of the beam size that can be measured at one position of the VWM. To enlarge the range of the measurement, it is preferable to use wires with smaller diameter and longer length (in our case, it was $100 \mu \mathrm{~m}$ in diameter and 80 mm in length). The amplitude of wire oscillation can also be increased by slightly increasing the oscillation excitation current.

Using estimations in the regression process, we can evaluate the signal to noise ratio (SNR) for the present measurements. For each


FIG. 11. After applying shift $=1.012$, two datasets from VWM positions -0.11 mm and -0.04 mm overlapped. The transverse coordinate is measured in units of oscillation amplitude and referenced to the VWM position -0.04 mm .


FIG. 12. Profile of the laser beam in absolute units ( mm ). The profile is recovered by measurements at VWM positions -0.04 mm and -0.11 mm . The transverse coordinates are referenced to the VWM position -0.04 mm . Blue dots-profile recovered from measurement at the VWM position -0.04 mm , orange dots-profile recovered from measurement at the VWM position -0.11 mm .
measurement position of the VWM, we consider the mean square error of the processed experimental data presented in Tables I and II (i.e., parameter Err) as a level of background noise. For each case, the value of Err is about $3.25 \times 10^{-04}$, which defines the SNR to be about $3000(35 \mathrm{~dB})$. It is interesting to compare this value with the SNR estimated for "raw" experimental data (i.e., with parameters $\left.\tau=\varphi_{0}=0\right)$. By repeating all the steps of the second order polynomial regression, we find Err about $2.5 \times 10^{-03}$ which yields the SNR about 393 ( 26 dB ).

We should also note that, in principle, the present algorithm of measuring at two different VWM positions is required only for correct positioning of the sensor and absolute calibration of the wire amplitude oscillations.

## DISCUSSION

The proposed thin beam profile measurement method was experimentally tested on a focused laser beam with the use of upgraded electronics with a considerably small time constant. To improve the measurements further, wires with smaller diameters should be used.

The resolution of the proposed method is essentially defined by the characteristics of the measurement system used. In this study, a photodiode with custom-made electronics which contains an amplifier with adjustable gain was applied. The raw data obtained in this setup were rather noisy. It seems that the main source of the fluctuations in the raw data was the insufficient number of measurements by only 12 bit ADC during the oscillation period (i.e., for one measurement time about $12 \mu \mathrm{~s}$ and wire oscillation half-period about $828.5 \mu \mathrm{~s}$, the number of experimental points of one scan was only 66). Besides, measurements were performed using a high speed and high sensitive PIN photodiode but with not enough level of
accuracy. These circumstances were partly overcome by the extended data processing.

In the case of measuring beams of different origins (e.g., charged particles or hard electromagnetic radiation), one should use other types of measurement systems, such as photomultipliers which have their own resolution limits. Furthermore, the quantity of photons/secondary particles that reaches the measurement unit is essentially dependent on the type and energy of the beam and wire material used. So, the question of resolution limit will be discussed in further investigations for each case separately.

As for the upper limit of the measurable beam current/flux, we note that the limit is determined by the allowable overheating of the wire. For tungsten wires, the overheating limit is estimated about 600 K . This limit is associated with the decrease in the wire tension. Therefore, above this limit, the wire oscillation frequency drops to less than 1 kHz and becomes unstable. For stainless steel wires, allowable overheating is about 150 K .

Future works should focus on the design of a scheme to implement this method on the actual charged particle beams in accelerators. The bunch structure of the beam does not seem to be a major problem for the application of the proposed method. In a typical characteristic time scale of the measurement system (from $10 \mu \mathrm{~s}$ to 100 ns ), a great number of bunches with a time separation of about 0.3 ns (e.g., for long-pulse or continuous-wave (CW) electron beams from S-band accelerators) are captured. Hence, in this case, there is no distinction between DC and bunched beams. On the other hand, for beams with low bunch repetition rates, it will be necessary to develop a measurement scheme synchronized with the beam bunch structure.

It would be desirable to increase the operation speed of the measurement system, e.g., with the use of an ADC with a greater sampling rate. Also, online data processing procedures should be developed instead of the postprocessing of the accumulated data. In this case, we can take advantage of the fact that during one period of the wire oscillation, two scans occur in opposite directions. Therefore, the algorithm of comparing backward and forward scans can be used similar to the case of determining the terminal speed of the thermal type VWM. ${ }^{17}$ This comparison could lead to an additional correction of the profile.

Finally, it is emphasized that by the proposed method, it is possible to measure profiles of small transverse size beams ( $\ll 1 \mathrm{~mm}$ ) of various intensities within a characteristic time of about the wire's oscillation period (less than a millisecond).

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