

DESIGN FOR A FAST, XFEL-QUALITY WIRE SCANNER

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Abstract

RadiaBeam Technologies has designed and manufactured a new wire scanner for high-speed emittance measurements of XFEL-type beams of energy 139 MeV. Using three 25-micron thick tungsten wires, this wire scanner measures vertical and horizontal beam size as well as transverse spatial correlation in one pass. The intensity of the beam at a wire position is determined from emitted bremsstrahlung photons as measured by a BGO scintillator system. The wires are transported on a two-ended support structure moved by a ball-screw linear stage. The double-ended structure reduces vibrations in the wire holder, and the two-bellows design negates the effects of air pressure on the motion. The expected minimum beam size measurable by this system is on the order of 10 microns with 0.1-micron accuracy. To achieve this, new algorithms are presented that reduce the effect of the non-zero thickness of the wire on the wire scan output. In addition, novel calculations are presented for determining the elliptical geometric parameters (vertical and horizontal beam size and correlation, or alternatively, the axis lengths and rotation) of the beam from the wire scanner measurements.

WIRE SCANNER OPERATION

The prototype RadiaBeam wire scanner (see Fig. 1) operates by moving three tungsten wires transversely across the electron beam. When the beam impacts the wire, the interaction generates a pulse of bremsstrahlung photons in the 10 MeV range that emerges in a narrow cone around the downstream beam. These photons are absorbed and measured by a bismuth germanium oxide (BGO) scintillator system to measure the total energy of the gamma pulse. This total energy is proportional to the integrated intensity of the beam at the location of the wire. The beam widths measured by horizontal, vertical, and 45-degree wires allow for the determination of the beam widths and other transverse geometric properties.

MECHANICAL DESIGN

Tungsten Wire

Tungsten wire was chosen for its high tensile strength (to ease installation by hand), high melting point (to withstand the high energy beam), and short radiation length due to its high mass number and density (to generate a larger number of photons). The high tensile strength of tungsten also allows for a higher tension in the wire to reduce sag and raise the fundamental mode of vibration above that of any nearby vibration sources like the linear motor. The three

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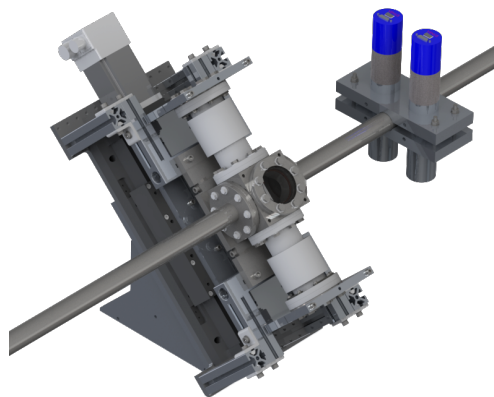


Figure 1: Complete wire scanner structure.

wires are angled 45 degrees from each other, resulting in a vertical, diagonal, and horizontal wire assembly that will be sufficient to reconstruct the transverse profile of an elliptical beam.

Ceramic Wire Holder

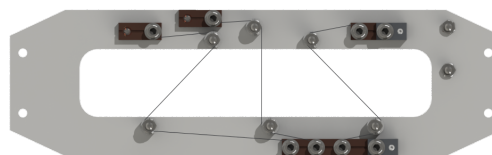


Figure 2: Wire holder.

The wire holder (shown in Fig. 2) was manufactured from alumina to counter problems with wire breakage due to RF heating experienced in wire scanners at CERN [1] and SLAC [2]. The insulating material also allows for monitoring of the wires through their electrical resistance. Each tungsten wire is connected to an SMA feedthrough on the lower end flange to allow an ohmmeter to check the wire integrity. An increase in resistance indicates the wire is heating up and possibly stretching. An open circuit indicates the wire has broken.

The aperture in the wire holder allows for a maximum 25-mm width beam to pass through. The wires are spaced such that, even with a maximum-sized beam, only one wire will interact with the beam at once, thus preventing bremsstrahlung photons from more than one wire being detected from a single beam pulse.

Vacuum Chamber Design

The wire holder is supported at both ends by plates fastened to the end flanges. These end flanges are connected

to the central vacuum cube by a pair of bellows. This double-ended setup reduces transverse vibrations and increases system stiffness compared to a single-ended support structure. It also cancels the effect of air pressure on the motion as both ends of the bellows system move together.

Linear Stage and Position Measurement

The wire assembly is moved by an Aerotech PRO225 ball-screw linear stage with a 1000-line amplified sine wave encoder capable of reporting its position with an accuracy of 1.5 microns. The controller, an Aerotech Soloist CP10-MXU, allows for input trigger signals to synchronize measurements with the scintillator assembly.

Scintillator Detectors

The bremsstrahlung gamma ray pulses are detected by a BGO scintillator assembly comprised of a 59-mm diameter \times 180-mm length BGO crystal, a Hamamatsu R6231 photomultiplier tube (PMT), and a Canberra Osprey multichannel analyzer (MCA). The large crystal was chosen for two reasons: (1) the large diameter will absorb nearly all incident gamma photons, and (2) the long length allows the PMT and MCA to be placed out of the way of the gamma photons, reducing false readings and radiation damage to electronics. Two of these assemblies are mounted on either side of the downstream beam pipe to reduce the effect of an off-center beam on the detected signal. The MCA is operated in pulse height mode in order to measure the total energy of the pulse.

The spectrum of energies is irrelevant to wire scanner measurements. In fact, the spectrum should be the same for every pulse, with only the intensity changing. Despite this, a multichannel analyzer is needed since the energies of individual photons are irresolvable due to the shortness of the pulse. Only the total energy of the pulse will be recorded as if it was from a single photon, resulting in a series of measurements of a wide range of energies.

Integrated System

The full wire scanner communication system is diagrammed in Fig. 3. The trigger source synchronizes the beam pulses with the position and gamma photon measurements.

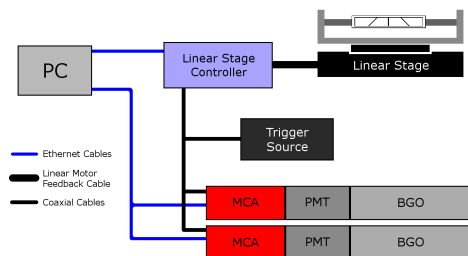


Figure 3: Communication layout of wire scanner system.

SIMULATED WIRE SCANNER OUTPUT ANALYSIS

Recovery of Transverse Beam Geometry

Assuming an elliptical transverse beam profile, the widths measured by the wire scanner are shown in Fig. 4. If the transverse shape is to be represented as a covariance

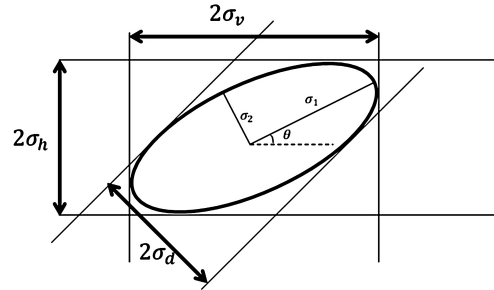


Figure 4: Geometry of wire scan.

matrix, this is given by

$$\begin{aligned} \Sigma &= \begin{bmatrix} \sigma_x^2 & \sigma_{xy} \\ \sigma_{xy} & \sigma_y^2 \end{bmatrix} \\ &= \begin{bmatrix} \frac{1}{2}(\sigma_h^2 + \sigma_v^2) - \sigma_d^2 & \frac{1}{2}(\sigma_h^2 - \sigma_v^2) \\ \frac{1}{2}(\sigma_h^2 - \sigma_v^2) & \frac{1}{2}(\sigma_h^2 + \sigma_v^2) - \sigma_d^2 \end{bmatrix} \quad (1) \end{aligned}$$

where each σ refers to an RMS half-width. σ_x and σ_y are the beam widths in the horizontal and vertical directions in the lab frame; σ_{xy} is the covariance of the beam intensity in x and y ; σ_v , σ_d , and σ_h are the beam widths as measured by the vertical, diagonal, and horizontal wires. The correlation, ρ , between the intensity distributions in x and y can be expressed as

$$\rho = \frac{\sigma_{xy}}{\sigma_x \sigma_y} = \frac{(\sigma_h^2 + \sigma_v^2) - 2\sigma_d^2}{2\sigma_v \sigma_h}.$$

If the transverse shape is to be represented as an ellipse with semi-axes σ_1 and σ_2 rotated by an angle θ , these parameters are given by

$$\begin{aligned} \tan \theta &= -\frac{\sigma_v^2 - \sigma_h^2}{2\sigma_d^2 - (\sigma_v^2 + \sigma_h^2)} \\ &\pm \sqrt{\left(\frac{\sigma_v^2 - \sigma_h^2}{2\sigma_d^2 - (\sigma_v^2 + \sigma_h^2)}\right)^2 + 1} \quad (2) \end{aligned}$$

$$\sigma_1^2 = \frac{1}{2} \left[(\sigma_v^2 + \sigma_h^2) + (\sigma_v^2 - \sigma_h^2) \left(\frac{1 + \tan^2 \theta}{1 - \tan^2 \theta} \right) \right] \quad (3)$$

$$\sigma_2^2 = \frac{1}{2} \left[(\sigma_v^2 + \sigma_h^2) - (\sigma_v^2 - \sigma_h^2) \left(\frac{1 + \tan^2 \theta}{1 - \tan^2 \theta} \right) \right] \quad (4)$$

The choice of $+/-$ in the Equation (2) does not change the ellipse. Rather, it switches the axis labels (σ_1 and σ_2) and changes the rotation angle by 90 degrees. The result is an equivalent description of the same ellipse.

Simulated Data

Figure 5 shows a simulated run from a wire scan on a beam shown in the left-hand side of Fig. 6. The right-hand side of Fig. 6 shows the resulting restored beam.

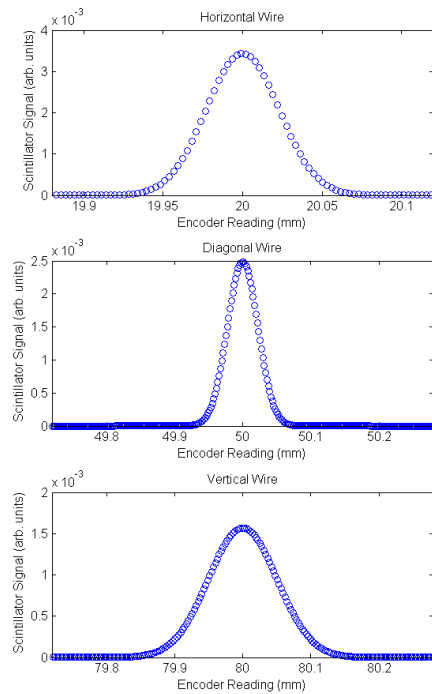


Figure 5: Simulated data from a wire scanner run.

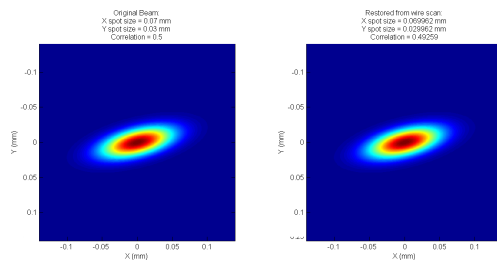


Figure 6: Comparison between the original simulated beam (left) and the beam recovered from the wire scanner data (right).

Finite Wire Thickness Correction

In the simulated example in the previous section, it can be seen that for beams larger than the wire, a Gaussian profile beam produces Gaussian-shaped scans. However, if the beam is smaller than the wire, the scan will more reflect the diameter of the wire, rather than the size of the beam. [3] This is because a real wire scan is actually a convolution of the beam width with the wire thickness (see Equation (5)).

$$m(x) = \int_{-\infty}^{\infty} f(x')w(x' - x)dx' \quad (5)$$

Here, $m(x)$ is the measured gamma signal as a function of wire position, $f(x)$ is the result of an ideal wire scan with a zero-width wire (assumed to be Gaussian for these simulations), and $w(x)$ is the radiation emitted by an electron impacting the wire at a distance x from the center. The radiation response for a cylindrical wire is given in Equation (6)

$$w(x) = \begin{cases} 1 - e^{-\frac{2\sqrt{r^2-x^2}}{l}} & \text{if } |x| < r \\ 0 & \text{if } |x| > r \end{cases} \quad (6)$$

where l is the radiation length of the wire material at the relevant beam energy, r is the radius of the wire, and x is the transverse position of the wire. Fitting to Equation (5) should give more accurate results than a regular Gaussian fit for small beam sizes (it should always give more accurate results, but the effect of the wire thickness becomes negligible for beams several times larger than the wire diameter). Simulated scans result in accurate ($< 5\%$ error) measurements of beams ten microns across with a 25-micron wire.

FUTURE IMPROVEMENTS

To further reduce vibrations and improve positional measurement accuracy, the next version of the RadiaBeam wire scanner will use a direct linear motor stage with a linear encoder. To accommodate the lower force output of such motors, a horizontal motion scanner is being considered. A horizontal motion scan will necessarily have no horizontal wire for directly measuring the vertical beam size (σ_y). However, a scan with a vertical wire and two diagonal wires can yield the same information as Equations (1)–(4) with a simple coordinate rotation.

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