FIRST VIBRATING WIRE MONITOR MEASUREMENTS OF A HARD X-RAY UNDULATOR BEAM AT THE ADVANCED PHOTON SOURCE*

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Abstract

The first hard x-ray flux measurements with a vibrating wire monitor (VWM) using the acoustic resonance frequencies of two vertically-offset horizontal stainless steel wires as temperature diagnostics were conducted at APS beamline 19-ID. Due to the high sensitivity of this technique, the studies were performed at extremely low power levels using radiation from a 3.3-cm-period permanent magnet hybrid undulator with a 5-mA electron beam at an energy of 7 GeV. The x-ray beam was filtered by transmission through 7 mm of beryllium placed in the photon beam path, assuring that only hard x-rays were detected. The particle beam was scanned through a range of 200 microradians using an asymmetric closed-orbit angle bump, producing two vertical photon beam profiles. The difference between processed wire signals provides a very sensitive measure of photon beam position. Details of the measurements will be given, along with a discussion of the limitations of the method and possible future research directions.

INTRODUCTION

The use of a vibrating wire monitor as a diagnostic for the determination of particle beam transverse profiles was suggested in 1999 [1] and first demonstrated using a 6-nA electron beam at an energy of 20 MeV in 2002 [2]. This work has expanded to measurements of ion beams and halo measurements of proton beams [3]. The VWM has shown sensitivity to temperature changes at the level of 0.001 K, making it well suited to beam halo measurements. In the case of charged particle beams, the electromagnetic interaction between beam and wire requires special care in the interpretation of the data.

At the Advanced Photon Source (APS), a significant effort has been put into the development of ultraviolet (UV) photon beam position monitors (BPMs) for both bending magnet and insertion device (ID) beamlines [4,5]. Use of these monitors has been instrumental in the achievement of sub-microradian-scale long-term pointing stability. Because they are sensitive to UV radiation, however, significant systematic errors caused by stray bending magnet radiation affect the signals for ID photon BPMs.

To further improve ID beamline stability, an effort to develop beam position monitors that are sensitive only to hard x-rays was initiated in 2005. A spare vacuum vessel at APS beamline 19-ID was instrumented with water-cooled mounting plates, translation stages, and electrical feedthroughs, to test a number of different concepts [6,7]. This vacuum vessel is located approximately 52 meters downstream of an ID source point, allowing low power tests with hard x-ray beams to be conducted with sensitivity to extremely small steering errors, owing to the long lever arm. A rectangular 2.1 x 4.2 mm aperture is located approximately 1 meter upstream of the detector mount.

VWM DESIGN

Shown in Figure 1 is a diagram of the VWM as assembled for the APS experiment. Two horizontally-mounted 3.6-cm-long, 100-micron-diameter stainless steel wires with approximately 1.75-mm vertical separation were stretched across the beam, which passed through a 5-mm-diameter hole. Permanent magnets internal to the device introduce a magnetic field parallel to the beam on one side and antiparallel on the other. With this configuration, an AC flowing along each wire efficiently couples to the wire's second-harmonic acoustic resonance. A simple positive feedback circuit to excite the resonance together with a counting circuit was used to measure the resonance frequency. As the wire temperature changes, this frequency shifts as a consequence of the changing wire tension according to the formula

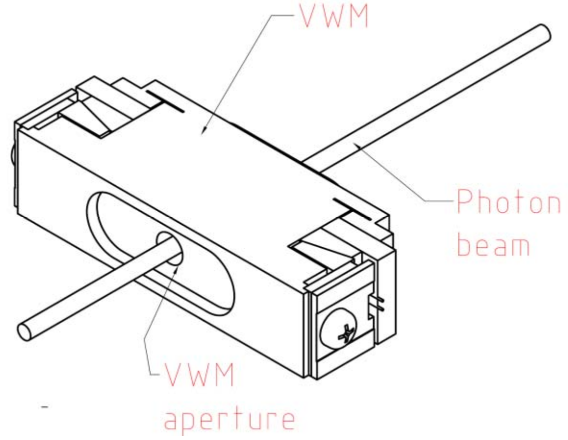

Figure 1. Vibrating wire monitor installed at APS beamline 19-ID.

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$$\Delta T_{MAX} = -4\frac{f - f_0}{f_0 E \alpha_S}\sigma_0 \; ; with \;\; \sigma_0 = f_0^2 l^2 \rho \;, \qquad (1)$$

where ΔT_{MAX} is the maximum wire temperature assuming a triangular profile along the wire, f_0 is the initial wire resonance frequency, f is the frequency after heating, E is the modulus of elasticity (2e11 Pa for stainless steel), α_S is the thermal expansion coefficient (1.75e-5 K^{-1}), ρ is the density (8e3 kg/m^3), σ_0 is the initial wire stress, and l is the wire length (3.6 cm) [3]. This assumes that the wire support structure is held at fixed temperature. A small water temperature regulation system was used to keep the support temperature stable at the ±0.05 K level. With the detector installed in vacuum, the initial resonance frequencies f_0 of the two wires were approximately 4005 Hz (wire C) and 5149 Hz (wire D), respectively, a result of differing initial wire tension.

EXPERIMENTAL RESULTS

A total of 5 mA of electrons were stored in 12 equally-spaced bunches in the APS storage ring, using a square-response-matrix-orbit-correction algorithm with 80 narrow-band rf BPMs and 80 steering corrector magnets in both the horizontal and vertical planes to control the orbit. The BPMs chosen were mounted at opposite ends of the small-gap ID vacuum chambers, assuring the best resolution and control of the ID source points.

With the ID gap open, i.e., with zero field, UV bending magnet radiation originating from steering correctors located immediately upstream and downstream of the ID propagated down the ID beamline [5] and was detected by the wires as a decrease in frequency of 44 Hz (wire C) and 35 Hz (wire D), respectively. This followed a detailed alignment procedure to assure that both wires were symmetrically placed above and below the accelerator midplane with a clear line of sight to the source. After inserting a 1-mm-thick Beryllium filter upstream of the detector into the beam path, the wire temperatures returned to their closed-shutter values, indicating that only soft UV radiation was present. Using equation (1), the observed frequency shifts correspond to a temperature change of 2.2 K, showing the extreme sensitivity of this detector. The corrector peak field was 1.4 kG; however, they have an extensive fringe field, and this fringe field was the actual source of the observed radiation.

For the insertion device tests, a total of 7 mm of Beryllium was placed in the beam path, both to limit the power striking the wires and to assure that only hard x-rays were being detected. The insertion device used was a standard APS undulator A, capable of producing over 5 kW total power in a beam a few mm high and a couple of cm wide at 52 meters from the source with 100 mA of stored beam current. The field increases approximately exponentially as the ID gap is decreased to a minimum of 11 mm. The wire monitors first detected the beam at a gap of 80 mm, and registered a frequency shift of 1.5 / 2.0 kHz with a gap of 45 mm, which was the smallest used for fear of destroying the wires. Equation (1) indicates that the wire temperatures at this point had risen by somewhere in the range of 90 to 103 K; however the frequencies did not return to their original values when the shutter was closed. This seems to show that the wire properties were changed by exposure to the relatively high flux of hard x-rays. The new "cold" wire frequencies were 4161 Hz and 5223 Hz, somewhat higher than at the start. For the remainder of the measurements, a gap of 60 mm was chosen to give a modest temperature rise of 5.4 K when the photon shutter was opened. It should be noted that the initial alignment using corrector fringe field radiation did a good job of aligning the ID beam between the wires.

Shown in Figure 2 are data collected at a 1-Hz sample rate during a scan of the particle beam's vertical angle under the conditions just described.

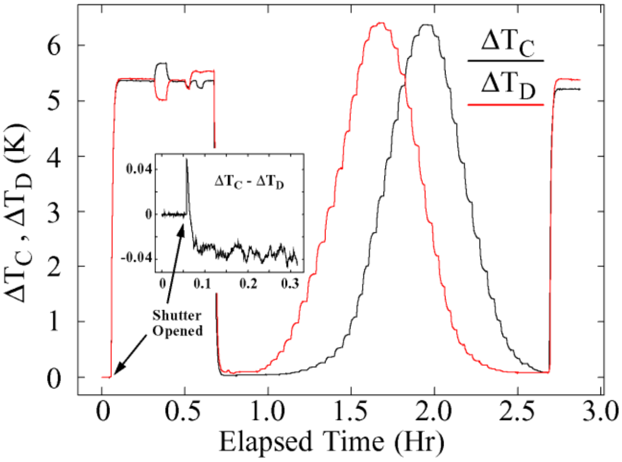

Figure 2. Data collected during vertical angle scan.

The initial frequencies f_0 for the two wires were determined with the shutter closed at the start of the scan. Using these values, the temperature changes ΔT_C and ΔT_D were determined using equation (1), and these values are plotted in Figure 2. After some initial steering tests, the beam was steered downward by 100 microradians (0.6 hours after shutter opening) and then steered upward in 5-microradian steps over the course of the next two hours, after which it was steered back to center. Because the primary mechanisms for cooling are conduction and radiation, it required about 3 minutes for the wire temperatures to achieve steady state following each steering change. During the two hours, the beam current decayed by about 3% from 4.53 to 4.38 mA.

A magnified view of the difference ΔT_C - ΔT_D is shown in the inset of Figure 2. With the shutter closed, the fluctuations fall in the range ±0.001 K, while after opening the shutter with the beam approximately centered, the fluctuations are significantly larger, most likely the result of real beam motion. At the detector location, this ±0.001 K translates into a noise floor near 0.5 microns p-p. Considering the 52 meter distance from the source, this translates into less than 10 nanoradians of p-p angular resolution, which is quite remarkable.

To process the data, it was subdivided into 43 separate files for each step and each segment was fit to a function of the form ΔT = Constant + Factor × exp(-Rate × Time) for each wire. The readbacks from the BPMs straddling the source were averaged for each segment, and an angle was computed from their difference. Multiplying this angle by the 52-meter source-detector distance resulted in an effective beam position value projected to the detector location. Because some segments of the exponential fit were essentially constant, they gave an inaccurate determination of the Rate, so a second pass of fitting was used, with the Rate constrained to equal the average value for all the good segments. A plot of Constant fit value vs. position then gives a good first-cut representation of the x-ray beam profile. The time constant = Rate^{-1} was 30.5 seconds and 30.9 seconds for wires C and D, respectively, using this method. The Constant vs. position data for each wire was then fit to a Gaussian to extract a centroid position and sigma. To extract thermal drift, the sum of the Constants for the two wires was fit to a constrained sum of Gaussians with an additive linear function of time representing the drift, using centroid and sigma values from the previous separate-Gaussian fit. This drift was then subtracted from the original Constant vs. position data, which then was normalized to the average beam current for the data set, producing a second-cut x-ray profile, corrected for thermal drift and beam current decay. The thermal drift amounted to a DC level shift of 0.01 K (relative to time zero of Figure 1) with 0.01 K / hour variation. While the linear thermal drift model is incorrect in detail, this approach at least gives some idea of the scale of the effect and is required prior to beam current normalization to achieve the best accuracy. The results are shown in Figure 3. The plot of ΔT_D was shifted by 1.730 mm in the lower plot, determined from the difference in centroid positions from the Gaussian fits. The wire separation measured later with a microscope was 1.717±.001 mm.

DISCUSSION

The above detailed analysis was conducted with the aim of determining the x-ray beam profile with the best accuracy possible. Insofar as the thermal drift of the two wires track each other and considering that the beam position is related to the temperature difference between the wires, this effect tends to cancel when using this device as a BPM. The observation that the DC baseline on the right-hand side of the profiles falls only to 0.03 K is simply an indication of the inaccuracy of the thermal drift compensation model chosen and does not directly impact the usefulness of this device as a BPM. At the very end of studies the photon shutter was closed, and both wires indicated that the ambient temperature had drifted up by 0.09 K over the 3.5-hour experiment duration. Unfortunately, there was also a difference of 0.008 K between the wires, which would translate directly into a 2-micron position measurement error given the parameters of the experiment. Whether there was a real temperature gradient across the device or a drift in the detection electronics is a subject for further study. Inclusion of additional well-shielded wires to measure local thermal drifts may be a solution.

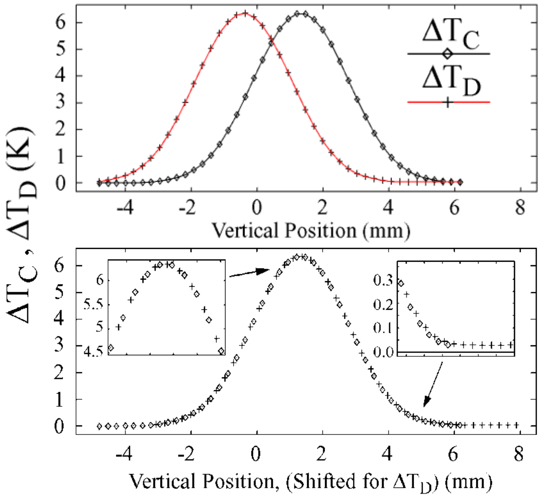

Figure 3. VWM data corrected for thermal drift and beam current decay. The two data sets are offset in the lower panel for direct comparison.

It is clear that the limitations of this device as tested are the slow response time and the power-handling capability. Some of these issues are discussed in a separate paper [8]. Given the extreme sensitivity of this device, one could consider placing it outside of vacuum to detect only very hard x-rays that penetrate the chamber at selected locations [9]. The addition of convective cooling would reduce the response time substantially albeit with reduced sensitivity. This would in addition reduce costs by a large factor. Incorporation of such a device into the design of water-cooled beamline apertures with judicious shielding – a so-called "smart aperture" – is another interesting concept. As a hard x-ray detector, the VWM concept shows a lot of promise due to its very high sensitivity and overall simplicity in both the mechanical design and front-end electronics.

REFERENCES

[1] S. Arutunian, et al., *Phys. Rev. ST Accel. Beams* **2**, 122801 (1999).
[2] S.G. Arutunian, N.M. Dobrovolosk, M.R. Mailian, and I.E. Vasiniuk, *Phys. Rev. ST Accel. Beams* **6**, 042801 (2003).
[3] S.G. Arutunian, M.R. Mailian, Kay Wittenburg, *Nucl. Instrum. Methods A* **572**, 1022-1032 (2007).
[4] G. Decker, O. Singh, PAC '01, Chicago, IL (2001).
[5] G. Decker, O. Singh, *Phys. Rev. ST Accel. Beams* **2**, 112801 (1999).
[6] R. Alkire, G. Rosenbaum, and G. Evans, *J. Synchrotron Rad.* **7**, 61-68 (2000).
[7] G. Decker, G. Rosenbaum, and O. Singh, BIW '06, Batavia, IL, AIP Conf. Proc. 868, 202-207 (2006).
[8] S. Arutunian et al., these proceeedings.
[9] B.K. Scheidt, DIPAC '05, Lyon, France (2005).