A WIRE SCANNER DESIGN FOR ELECTRON BEAM PROFILE MEASUREMENT IN THE LINAC COHERENT LIGHT SOURCE UNDULATOR*

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Abstract

The Linac Coherent Light Source (LCLS), currently under design, requires beam diagnostic instruments between the magnets in the beam undulator section. Ten wire scanners are planned as one of the primary instruments to characterize electron beam properties. The development of these wire scanners presents several design challenges due to the need for high accuracy and resolution of the wire motion (3-μm tolerance, typical) and the high intensity of the beam (1 nC, 3400-A peak, over an area of 30-μm rms radius at 120 Hz). In this paper, we present the technical specification and design criteria for the scanners. We will also present the mechanical design of the UHV-compatible drive and its engineering analysis. Lastly, we present the wire card design and discuss associated thermal and mechanical issues originating from the highly intense x-ray and electron beams.

INTRODUCTION

The Linac Coherent Light Source (LCLS), currently under design, requires beam diagnostic instruments between the magnets in the beam undulator section. Ten wire scanners are intended to characterize electron beam properties.

The primary purpose of the system is to provide high-resolution measurement of electron beam profile averaged over many shots. It is based on 1) direct interaction of the electron beam with a thin wire and 2) the assumption that the flux of the secondary product is proportional to the intensity of the electron beam passing through the wire. The secondary products currently include scattered high-energy electrons, gamma-ray photons, and secondary-electron current.

The design described herein is for portions of the undulator where free-electron laser (FEL) intensity is not strong enough to damage the wire. The development of practical and reliable wire scanners that meet the required positioning accuracy, survivability under the severe beam conditions, and operation in an ultrahigh-vacuum environment present several engineering design challenges.

SPECIFICATIONS

We derived the specifications of the wire scanner from the electron beam parameters for LCLS undulators [1]. Table 1 gives the relevant operating parameters.

*Work supported by the U.S. Department of Energy, under Contract Nos. W-31-109-ENG-38 and DE-AC03-76SF00515.

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Table 1: Operating Parameters of the LCLS Undulator Wire Scanner Design

Parameter	Nominal	Maximum	Units
Beam intensity	1.2×10^9	6×10^9	electrons/bunch
Peak particle density	1.5×10^5	7.3×10^5	e/μm²/bunch
Electron bunch energy	2.7	13.64	Joule/bunch
Electron bunch momentum	0.9×10^{-8}	4.5×10^{-8}	kg-m/s / bunch
Beam Size Sigma	32	55	μm

Spatial Resolution

The spatial resolution is the most important performance specification of the profile measurement system. With the current design, the rms electron beam sizes in the undulator will be from 37 μm (at 13.6 GeV) to 55 μm (at 4.3 GeV). A 12-μm rms system resolution will be sufficient for accurate measurement of the beam profile. Because the measured beam size is the quadrature sum of the true beam size, an rms system resolution of 12 μm would give us an error bar of 5%, or 2 μm out of 37 μm.

Many factors contribute to the system resolution. A simple-minded model gives us the following expression for rms resolution of the wire scanner system,

$$\sigma_{reso}^2 = \left(\frac{D}{4}\right)^2 + \sigma_{vib,wire}^2 + \sigma_{vib,mount}^2 + \sigma_{motion}^2 + \ldots,$$

where D is the diameter of the wire, $\sigma_{vib,wire}$ is the rms vibration amplitude of the wire, $\sigma_{vib,mount}$ is the rms vibration amplitude of the mounting mechanism, σ_{motion} is the rms error of the random error of the scanning mechanism, etc. Based on this expression, we make the following secondary specifications.

Wire Mechanical Specifications

Table 2 lists our budget for contributing factors of resolution. The positioning increment (step size for stepper drive, and encoder resolution for servo drive) should be 0.5 μm or less for smooth motion at the data scan. An independent position read back will be provided in the case of the stepper drive. The read back will have a

0-7803-8859-3/05/$20.00

resolution of 1 µm or better. When a relative encoder is used to readout the positions, the repeatability of the home position (typically via limit switch or home switch) should be within 15 µm, peak to peak. Within the range of profile measurement, the scanner speed should fall between 20 µm/s and 240 µm/s. The scanning speed should be adjustable remotely within this range. The motion of the wire scanning mechanism will have sufficient stroke to be away from the beam so that it does not interfere with the insertion of the wakefield shield during normal FEL operations.

Table 2: Partial Resolution Budget

Source	Limit	Resolution
Finite wire size (diameter)	30 µm	7.5 µm
Wire vibration amplitude (rms)*	5 µm	5 µm
Wire mount vibration amplitude (rms)*	5 µm	5 µm
Wire mount motion error (rms)*	5 µm	6 µm
Total		12 µm

*Measured only in the direction perpendicular to both the wire and the beam.

MECHANICAL DESIGN

The design of the prototype wire scanner is shown in Figure 1. It consists of a body with vacuum seal mounting flange and bellows, a linear slide, linear actuator, encoder, and wire card. The slide, actuator, and encoder are located external from the ultrahigh-vacuum environment.

The flange, bellows, and wire card assembly are required to meet the ultrahigh-vacuum requirements. The assembly is designed to allow for removal of the slide, actuator, and encoder for bake out of the vacuum components. The vacuum components are designed to withstand a 125°C bake-out temperature.

The linear guide and actuator are selected to provide the required accuracies given above in the wire specification section. The linear slide has an overall stroke of 50 mm and is designed to meet a required load static moment capacity of 2.5 N-M with an additional 12 N-M allowed for a dynamic or accidental moment load.

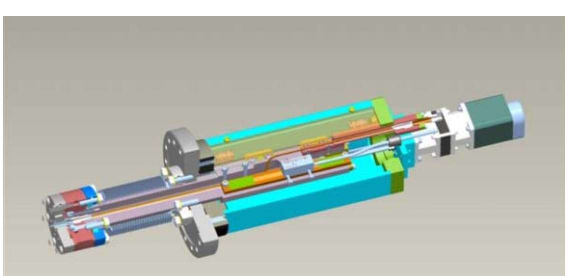

Figure 1: Wire scanner prototype—¼ section (wire card not shown).

The linear actuator is selected to provide a 22-kg force, which is required to overcome the vacuum force and still maintain the accuracy indicated in the wire specification section.

Two encoders are installed on the prototype for testing purposes. A rotary encoder is mounted on the back of the drive motor and a linear encoder is located within the body. The encoders are selected to provide a resolution of less than 1 µm. Prototype tests will determine which encoder is best suited for this application.

WIRE BREAKAGE STUDY

Background

Wire scanner monitor instruments currently used in the Stanford Linear Collider (SLC) have a history of wire failures due to high-power electron beam interaction with the scanning wire. The specific mechanism that causes these failures has not been determined [2]. The LCLS electron beam will have similar beam parameters to that of the SLC; therefore, chronic wire failures in the wire scanners for the LCLS are of concern. A better understanding of the wire failure mechanism is essential to the design of reliable LCLS scanners. Several breakage scenarios have been set forth. A was study performed [2] that suggests the failures may be caused by electrical arcing at the wire supports due to high impedance in the wire connection assembly. However, tests using solder mounts that minimize the impedance still result in identical failures [2] and, thus, the electrical arcing scenario is at best uncertain. It is the purpose of this study to investigate the possibility that wire failures are caused by fatigue stress at the wire mounts. Currently, this study is a work in progress; however, results to date are significant and are reported herein.

It is of fundamental interest that the wires fail at the wire mounts and not at the point of beam impingement. This suggests, at least from a mechanical proposition viewpoint, that a momentum transfer occurs from the beam through the wire to the wire mounting location. The momentum may be initiated at the point of beam impingement by either direct transfer of the electrons' momentum to the wire material or indirectly, by the sudden heating of the wire by the beam thus resulting in a thermal expansion shock wave moving through the wire.

Engineering Analysis

As a first step, several scenarios are analyzed for feasibility.

A transient heat transfer analysis was performed. As an initial condition, a Gaussian-shaped temperature profile was used with a sigma of 50 µm and a centerline temperature of 3000°C [2]. The results of this analysis indicate that the thermal relaxation response of the wire is approximately 10^{-4} seconds and that at a beam pulse rate of 120 Hz the entire wire essential returns to ambient temperature before the arrival of the next pulse.

Next, a dynamic structural traverse shock wave was analyzed. Direct momentum transfer from the electron beam to the wire may be significant, although physics calculations showing the possibility of this effect have yet to be performed. However, engineering analysis has been performed to determine the magnitude of the momentum transfer that would be required to fail the wire by fatigue stress. The structural dynamic analysis was performed. The initial dynamic condition of the wire immediately after the electron beam pulse was assumed to have zero displacement everywhere along the wire and zero velocity everywhere except near the center where a Gaussian velocity profile with a sigma of 50 µm was assumed. The magnitude of this profile was adjusted to produce a stress that would cause fatigue failure in the wire after approximately ten thousand loading cycles. The estimated number of cycles to failure is based on actual operating experience [2].

The results of this analysis are shown in Figures 2 and 3. The dynamic time response is shown to be on the order of 10^{-6} seconds after the electron beam pulse, which is significantly faster than that of the thermal response (10^{-4} seconds), indicating that the mechanical wave travel occurs while the wire is essential at the initial temperature condition. Thus, the mechanical properties of the wire such as Young's Modulus are known and constant during the mechanical wave motion. Figure 2 shows the overall wire displacement 4.0×10^{-6} seconds after the electron beam pulse. Based on the material properties for Tungsten wire, the strain required in the wire to cause failure after ten thousand cycles is approximately 0.1%. The analysis indicates this maximum strain will occur once near the center in less than 0.40×10^{-6}seconds after the beam pulse and then much later, as the wave reflects back and forth, this maximum strain will occur at the fixed ends at least twice. Figure 3 shows the strain contour at the fixed end at the first occurrence of the maximum strain. The significance of these results is that the maximum strain occurs at only two places in the wire, once near the center and at least twice at the fixed ends, indicating that a traverse wave of sufficient energy would cause fatigue failure of the wire at the fixed ends. Also, although the initial velocity required to fail the wire is surprising large (300 m/s) the corresponding kinetic energy of the wire appears to be reasonable in that it is very much less than the potential energy due to thermal expansion noted in the thermal analysis.

Analyses of a thermal shock wave due to thermal expansion and wire vibration due to wire card movement are planned. Also, prototype tests are planned to verify these analyses. Based on the results of this study, the design of the wire card will be finalized.

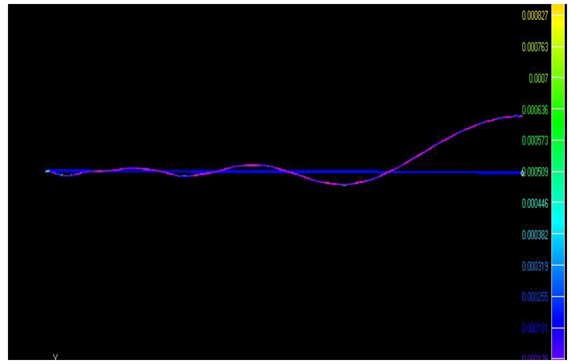

Figure 2: Traverse wave.

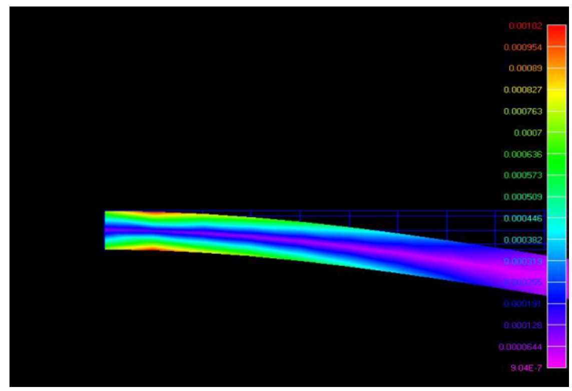

Figure 3: Fixed end.

SUMMARY

We have completed the design of the prototype wire scanner that will be used in the LCLS undulator. Pending results from the wire breakage study the wire card design will be finalized. After fabrication of the prototype, extensive bench and in-beam testing will be used to verify the adequacy of the design prior to first article production.

REFERENCES

[2] LCLS online parameter database, http://www-ssrl.slac.stanford.edu/htbin/rdbweb/LCLS_params_DB_public/.

[1] C. Field, D. McCormick, P. Raimondi, and M. Ross, "Wire Breakage in SLAC Wire Profile Monitors," BIW97, AIP Conf. Proc. 451, p. 440.

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