

# LCLS-II Undulator Vacuum Chamber Surface Roughness Evaluation 

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## 1 Introduction

Currently, the APS is producing the vacuum chambers for the LCLS-II undulator segments, using an Al extrusion process similar to the one used for the LCLS vacuum chambers. The polishing method used is an improved version of the one used for LCLS about 10 years ago to provide a more consistent surface finish of better quality. See the technical note by Greg Wiemerslage (APS) [1]. The technical description of the process in that note is reproduced here: It was shown that the surface finish of raw extrusions can be improved significantly by polishing the beam aperture using an extrude hone method. This method polishes the surface, but does not remove all imperfections in the surface such as longitudinal scratches created by the process which extrudes the raw material extrusions from the aluminum billet. The quantity and depth of these longitudinal scratches are minimized by mechanical polishing of the extrusion die. Raw surface finish samples are taken from each extrusion batch because it is understood that the extrusion process may cause slight differences from batch to batch due to material differences, wear on the die, temperature of the material during the run, etc. They can then compare the before polishing results to the after polishing results to verify the progress of the polishing efforts. During production polishing, they periodically perform destructive testing by taking a sample from the middle of an extrusion to verify that the middle of the extrusion is polished as evenly as the ends of the extrusion.
As delivered, the raw extrusion batch for the SXU vacuum chamber appeared to have some noticeable scratches, but nothing out of the ordinary. Upon further inspection, the surface finish had a measured average roughness $\mathrm{h}_{\mathrm{rms}}$ of $847 \mathrm{~nm}, \mathrm{a}(\mathrm{dh} / \mathrm{dx})_{\mathrm{rms}}$ of 201 mrad , and $\mathrm{a}(\mathrm{dh} / \mathrm{dz})_{\mathrm{mm}}$ of 71 mrad . Eighteen spots were measured. Three from each end along the top and bottom flat surfaces, and three from the top and bottom of the middle section of the extrusion. The specification (Functional Requirements Specification LCLSII-3.2-FR-0158) requires that the average of the longitudinal surface roughness, $(\mathrm{dh} / \mathrm{dz})_{r m s}$, of all vacuum chambers of be $<20 \mathrm{mrad}$, and the average of all chambers of the azimuthal surface roughness, $(\mathrm{dh} / \mathrm{dx})_{\mathrm{rss}}$, be $<50 \mathrm{mrad}$.
The surface roughness measurements are performed using a NexView profiler. The spot size of these measurements (the field of view (FOV) of the profilometer optic) was 0.61 mm by 0.61 mm . A sample was taken from each end of the polished extrusion and was split into two pieces revealing the inner surfaces of the aperture.
After polishing, the average of the $h_{r m s}$ values of thirty samples spots from the two extrusions polished during the polishing verification run improved to 198 nm , the average of the $(\mathrm{dh} / \mathrm{dx})_{\text {ms }}$ values improved to 28 nm , and the average if the $(\mathrm{dh} / \mathrm{dz})_{\text {rms }}$ values improved to 6 mrad , all well within the specifications of the functional requirements document.
On verification of the polishing process for the production batch of extrusions for the SXU vacuum chamber they noticed a few grooves on one side of the beam aperture. The grooves seem to run down the length of all samples that they had named top side of the extrusions. They don't know if the grooves are continuous along the extrusion or
whether they appear in all extrusions. Overall they find that if they average the entire flat surfaces of the beam aperture they find that the entire surface has an average $(\mathrm{dh} / \mathrm{dx})_{\mathrm{rms}}$ of 37.9 mrad and average $(\mathrm{dh} / \mathrm{dz})_{\mathrm{rms}}$ of 7.9 mrad , which is well within the allowable specification of LCLSII-3.2-FR-0158.

## 2 Surface Scan Results

To double check the findings, APS sent a number of surface samples to SLAC. The data from twelve surface scans carried out by May Ling NG at SLAC on unpolished and polished samples at the LCLS metrology lab have been made available for evaluation (see Figure 1 to Figure 12). The scans of unpolished samples (Figure 1, Figure 3, and Figure 5) show a random looking noise background on a somewhat bumpy structure with bump separations of order 1 um . The features are on top of shallow longitudinal grooves. The scans of the polished samples (Figure 2, Figure 4, Figure 6, Figure 7, Figure 8, Figure 9, Figure 10, Figure 11 and Figure 12) show none or very little of the random noise background. Instead, they are much smoother but show more systematic and larger longitudinal grooves produced by the polishing process. The roughness parameters for the scans are summarized in Table 1.

Table 1: Summary of SLAC scan results

| Fig. | Sample | $\mathrm{h}_{\mathrm{rms}}$ | $(\mathrm{dh} / \mathrm{dz})_{\mathrm{rms}}$ | $(\mathrm{dh} / \mathrm{dx})_{\mathrm{rms}}$ |
| :---: | :---: | :---: | :---: | :---: |
| 1 | top unpolished 2p75x center | 745 nm | 11 mrad | 33 mrad |
| 2 | top polished 2p75x center | 2407 nm | 4.0 mrad | 27 mrad |
| 3 | top unpolished 20x center | 378 nm | 63 mrad | 145 mrad |
| 4 | top polished 20x center | 503 nm | 12 mrad | 48 mrad |
| 5 | top unpolished 2p75x left | 613 nm | 11 mrad | 32 mrad |
| 6 | top polished 2p75x left | 1745 nm | 4.2 mrad | 23 mrad |
| 7 | top polished 2p75x center 2 | 2297 nm | 4.7 mrad | 26 mrad |
| 8 | top polished 20x center 2 | 574 nm | 8.3 mrad | 36 mrad |
| 9 | bottom polished 2p75x center | 407 nm | 1.5 mrad | 7.7 mrad |
| 10 | bottom polished 20x center | 107 nm | 4.0 mrad | 15 mrad |
| 11 | bottom polished 20x right | 340 nm | 8.1 mrad | 25 mrad |
| 12 | bottom polished 20xright 2 | 340 nm | 8.0 mrad | 25 mrad |

It is not clear how the locations and orientations of the unpolished samples are related to those of polished samples. For instance, Figure 1 has some similarity to Figure 2 if one of them is rotated by $180^{\circ}$ around the vertical axis.


Figure 1 top unpolished 2 p 75 x center: $\mathrm{hrms}=745 \mathrm{~nm},(\mathrm{dh} / \mathrm{dz})_{\mathrm{rms}}=11 \mathrm{mrad},(\mathrm{dh} / \mathrm{dx})_{\mathrm{rms}}=33 \mathrm{mrad}$


Figure 2 top polished 2p75x center: $\mathrm{h}_{\mathrm{rms}}=2407 \mathrm{~nm},(\mathrm{dh} / \mathrm{dz})_{\mathrm{rms}}=\mathbf{4 . 0} \mathrm{mrad},(\mathrm{dh} / \mathrm{dx})_{\mathrm{rms}}=\mathbf{2 7} \mathrm{mrad}$


Figure 3 top unpolished $20 x$ center: $h_{\text {rms }}=378 \mathrm{~nm}$, (dh/dz) $)_{\mathrm{rms}}=63 \mathrm{mrad},(\mathrm{dh} / \mathrm{dx})_{\mathrm{rms}}=145 \mathrm{mrad}$


Figure 4 top polished $20 x$ center: $\mathrm{h}_{\mathrm{rms}}=503 \mathrm{~nm},(\mathrm{dh} / \mathrm{dz})_{\mathrm{rms}}=12 \mathrm{mrad},(\mathrm{dh} / \mathrm{dx})_{\mathrm{rms}}=48 \mathrm{mrad}$


Figure 5 top unpolished 2p75x left: $h_{r m s}=613 \mathrm{~nm},(\mathrm{dh} / \mathrm{dz})_{\mathrm{rms}}=11 \mathrm{mrad},(\mathrm{dh} / \mathrm{dx})_{\mathrm{rms}}=32 \mathrm{mrad}$


Figure 6 top polished $2 p 75 x$ left: $h_{r m s}=1745 \mathrm{~nm},(\mathrm{dh} / \mathrm{dz})_{\mathrm{rms}}=4.2 \mathrm{mrad},(\mathrm{dh} / \mathrm{dx})_{\mathrm{rms}}=23 \mathrm{mrad}$


Figure 7 top polished 2 p 75 x center 2: $\mathrm{h}_{\mathrm{rms}}=2297 \mathrm{~nm},(\mathrm{dh} / \mathrm{dz})_{\mathrm{rms}}=\mathbf{4 . 7} \mathrm{mrad},(\mathrm{dh} / \mathrm{dx})_{\mathrm{rms}}=\mathbf{2 6} \mathbf{~ m r a d}$



Figure 8 top polished $20 x$ center 2: $h_{\text {rms }}=574 \mathrm{~nm},(\mathrm{dh} / \mathrm{dz})_{\mathrm{rms}}=8.3 \mathrm{mrad},(\mathrm{dh} / \mathrm{dx})_{\mathrm{rms}}=36 \mathrm{mrad}$


Figure 9 bottom polished 2 p 75 x center: $\mathrm{h}_{\mathrm{rms}}=407 \mathrm{~nm},(\mathrm{dh} / \mathrm{dz})_{\mathrm{rms}}=1.5 \mathrm{mrad},(\mathrm{dh} / \mathrm{dx})_{\mathrm{rms}}=7.7 \mathrm{mrad}$


Figure 10 bottom polished $20 x$ center: $\mathrm{h}_{\mathrm{rms}}=107 \mathrm{~nm},(\mathrm{dh} / \mathrm{dz})_{\mathrm{rms}}=4.0 \mathrm{mrad},(\mathrm{dh} / \mathrm{dx})_{\mathrm{rms}}=15 \mathrm{mrad}$


$$
\begin{array}{r}
0 \\
500 \\
0 \\
0 \\
0 \\
-500 \\
-1000
\end{array}
$$

Figure 11 bottom polished 20x right: $\mathrm{h}_{\mathrm{rms}}=\mathbf{3 4 0} \mathrm{nm},(\mathrm{dh} / \mathrm{dz})_{\mathrm{rms}}=8.0 \mathrm{mrad},(\mathrm{dh} / \mathrm{dx})_{\mathrm{rms}}=\mathbf{2 5 ~ m r a d}$


Figure 12 bottom polished 20x right 2: $\mathrm{h}_{\mathrm{rms}}=\mathbf{3 4 0} \mathrm{nm},(\mathrm{dh} / \mathrm{dz})_{\mathrm{rms}}=8.0 \mathrm{mrad},(\mathrm{dh} / \mathrm{dx})_{\mathrm{rms}}=\mathbf{2 5} \mathbf{~ m r a d}$

## 3 Evaluation and Conclusion

The surface roughness of the LCLS-II undulator vacuum chamber contributes to the overall wakefields, which can negatively impact the electron beam as it passes through. The wakefields are generated by the beam current acting on the vacuum chamber impedance. The surface of a very small section of the vacuum chamber above or below the beam axis can be described by $h(z, x)$, where $z$ is the surface coordinate in beam direction and $x$ is the surface coordinate in perpendicular to it. In the approximation of a perfectly conducting vacuum chamber material and a round cross section, the surface roughness impedance is proportional to

$$
\frac{Z_{0}}{c b^{2}} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{\kappa_{z}^{2}\left|\hat{h}\left(\kappa_{z}, \kappa_{x}\right)\right|^{2}}{\sqrt{\kappa_{z}^{2}+\kappa_{x}^{2}}} d \kappa_{z} d \kappa_{x}
$$

with the vacuum impedance, $Z_{0}$, the speed of light, $c$, the vacuum chamber radius, $b$, and the two dimensional Fourier transform of the surface profile function,

$$
\hat{h}\left(\kappa_{z}, \kappa_{x}\right)=\frac{1}{(2 \pi)^{2}} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} h(z, x) e^{-i \kappa_{z} z-i \kappa_{x} x} d z d x
$$

The typical values of $\kappa_{z}$ and $\kappa_{x}$ are related to the rms slopes

$$
\begin{aligned}
& \kappa_{z}=\frac{2}{h_{r m s}}\left\langle\frac{\partial h(z, x)}{\partial z}\right\rangle_{r m s} \\
& \kappa_{x}=\frac{2}{h_{r m s}}\left\langle\frac{\partial h(z, x)}{\partial x}\right\rangle_{r m s}
\end{aligned}
$$

Grooves in the longitudinal direction do not contribute to the surface roughness impedance, no matter what size, because they generate a spectrum with $\kappa_{z}=0$ and $\kappa_{x} \neq 0$, which does not add to the surface roughness impedance according to the first equation above, also see [2].

In conclusion: the roughness measurements of the polished samples as described in this report are all well within the LCLS-II undulator system vacuum chamber surface roughness tolerance requirements. The longitudinal grooves seen in Figure 2, Figure 4, Figure 6, Figure 7, Figure 8, Figure 9, Figure 10, Figure 11 and Figure 12 will not contribute to the surface roughness wakefields.

1 Greg Wiemerslage, "LCLS II SXRU vacuum chamber extrusion surface finish," Technical Note, 1/16/17
2 Gennady Stupakov et al., "Effects of Beam-Tube Roughness on X-Ray Free Electron Laser Performance," Phys Rev ST - ACCELERATORS AND BEAMS, VOLUME 2, 060701 (1999)

