DEVELOPMENT OF THE MANUFACTURING AND QA PROCESSES FOR THE MAGNETIC MODULES OF THE LCLS-II SOFT X-RAY UNDULATORS*

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Abstract

A new free electron laser being built at SLAC National Accelerator Laboratory, the Linear Coherent Light Source II (LCLS-II), will use 21 soft x-ray undulators (SXR) and 32 hard x-ray undulators (HGVPU). Lawrence Berkeley National Laboratory (LBNL) is responsible for the design and manufacturing of all variable-gap, hybrid permanent-magnet undulators. The physics requirements for the undulators specify a longitudinal pole misalignment maximum rms error of 25 µm and a vertical pole misalignment maximum error of 50 µm. In addition, magnet positioning critically influences the gap-dependent field properties due to saturation effects at the smallest operational gaps. This paper discusses the manufacturing and QA methods developed to carefully control the longitudinal and vertical pole and magnet positions during undulator production. Inspection results are discussed based on data gathered during construction of a prototype as well as pre-production soft x-ray undulator.

INTRODUCTION

The design of the SXR undulators includes requirements for the phase shake, effective field, first and second field integrals, given in Table 1 [1]. The allowable longitudinal and vertical variation in pole positioning was modelled, and the values in Table 2 were chosen to keep reduction in x-ray intensity due to pole positioning error to less than 0.75%.

Table 1: Basic Undulator Segment Tuning Requirements

Parameter	SXR Values	Unit
Phase shake (rms)	±5.0	deg
B_{eff} at minimum gap	>1.49	T
First field integral	<40	µTm
Second field integral	<150	μTm^2

Table 2: Undulator Segment Pole Position Tolerances

Parameter	SXR Values	Unit
Vertical magnet array straightness (rms)	<50	µm
Undulator period length variation (rms)	<25	µm

These parameters define the maximum vertical and longitudinal pole misalignment, without defining any requirements for magnet positioning. The prototype magnet modules [2] arrived at LBNL from Vacuumschmelze GmbH, Hanau, Germany, in March through May of 2015. The method of measuring and adjusting pole height was developed on these modules. It was determined that pole longitudinal positioning requirements were not being met and further work was necessary. Furthermore, the magnets on the SXR are 4 times larger than on the prototype by volume, and therefore difficulty with the assembly was anticipated for the pre-production SXR unit. The first SXR magnet modules were received by Keller Technology Corporation, Buffalo, NY (Keller) in April of 2016 and the ful undulator was measured at LBNL with Hall probe and flip coil in August 2016 [3]. Errors due to magnet height and longitudinal positioning led to changes to the assembly procedure for the first two production undulators, which were successfully delivered to SLAC National Accelerator Laboratory in April 2017.

POLE HEIGHT VERIFICATION

The design for the pole mounting [4] allows height adjustability. A flexure on either side of the pole, which is centered by pins in the module keeper, allows for ±100 µm of adjustability, see [4]. Our general approach to meeting pole height requirements is to measure two points on the top of the pole using a CMM, utilize these data to generate a list of relative adjustments if required, and then move each pole while tracking its position with two contact sensors. See Fig. 1 for CMM pole height data before and after adjustment.

This methodology was used for all four undulators that have been built at the time of this writing, but some refinements were made during the development of the assembly process for the prototype and the preproduction units as described below.

During our measurement of the prototype modules, we discovered that the 1052 mm long aluminium modules were flexible enough that we could not measure them consistently between vendors and LBNL without defining a specific clamping procedure. The top of the aluminium while unrestrained (Fig. 2) was flat to 39 µm, but flat to

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17 µm while restrained. In addition, Vacuumschmelze's initial method of clamping introduced a twist which contributed to discrepancies between the data taken in Germany and the data taken in California. These discoveries led to the clamping method as shown in Fig. 3, which is now employed for all production units.

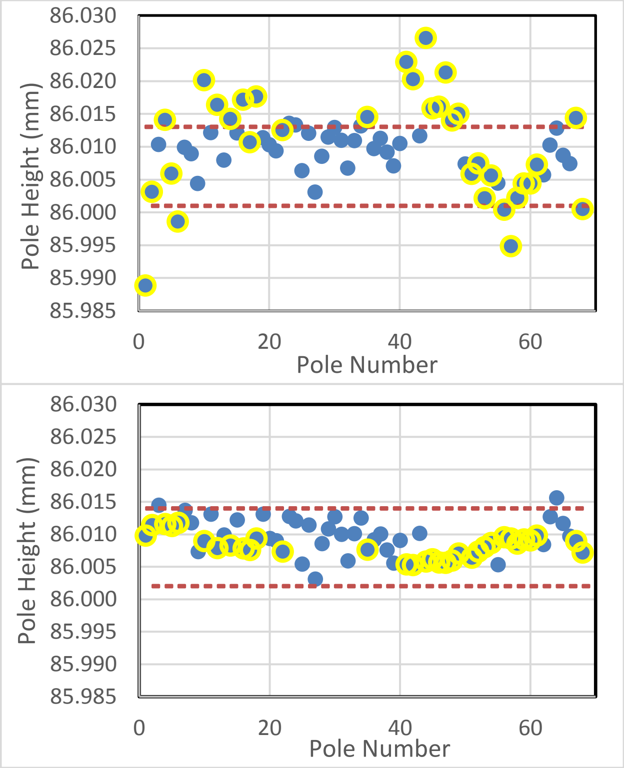

Figure 1: Left side pole height of module -006 of the prototype before and after adjustment. Points circled in yellow were adjusted. Right side pole height data was also taken, not shown.

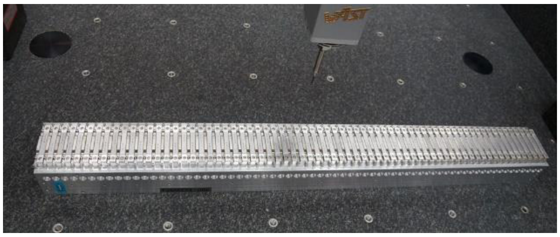

Figure 2: Unclamped magnet module.

Figure 3: Clamped magnet module.

We performed CMM measurements of the individual modules both before and after shipping on the prototype and pre-production SXR. After analysing the measurement data and the accuracy of the final CMM measurement of the full strongback (Fig. 4), the post-shipment measurement of individual modules was proven unnecessary, and that step was eliminated for the production SXRs.

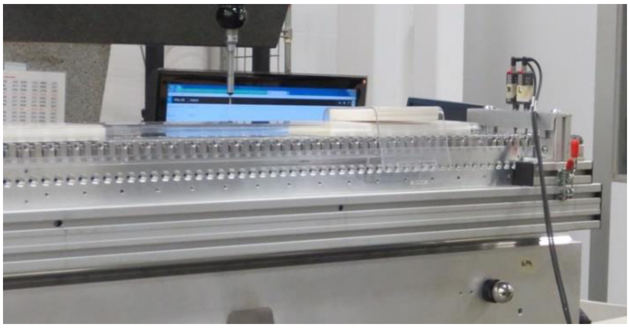

Figure 4: Magnet modules on CMM while attached to strongback. Shown with the two contact sensor fixture.

POLE SPACING VERIFICATION

Pole to pole spacing constitutes a difficult measurement for a CMM probe, as only the edge of the pole is exposed for probe pickup. The measurement can also be achieved with a camera (which is available at LBNL, but neither Vacuumschmelze nor Keller have this capability), or by using a probe small enough to fit inside the space left by a 4 mm chamfer. On the SXR, we decided resolve this difficulty by measuring pole position prior to inserting the magnets.

One of our design choices was to have no longitudinal adjustment built into the magnet module, and pin each pole flexure. The pin position has a tolerance of 30 µm and the pole position compared to the flexure has a tolerance of 10 µm. These tolerances should lead to the desired 25 µm RMS tolerance, but the pole to flexure position could only be restrained to 40 µm. This resulted in our prototype having a 30-46 µm RMS longitudinal error. However, we found that by sorting the poles based on the flexure distance from the front pole face, a 15 µm RMS error could be achieved, which is well within tolerances.

MAGNET HEIGHT IMPACTS

The SXR magnet positioning was designed to be 140 µm ± 40 µm below the pole heights, but the design allowed the mean pole height to float ±75 µm, as long as the poles remained flat compared to each other. This resulted in different mean pole height to mean magnet height measurements over the 6 periodic modules of the pre-production SXR as shown in Table 3.

Table 3: Difference Between Mean Pole & Magnet Heights

	Upstream	**Middle**	**Downstream**
Top	148 µm	169 µm	166 µm
Bottom	195 µm	185 µm	126 µm

During magnetic measurements of the pre-production undulator, a gap-dependent taper was observed. Figure 5 shows the maximum extent of the taper. It was theorized that the modules on one end of the undulator produced a weaker field than the modules on the other end, resulting in the taper. Considering the variation in pole-magnet height difference on the pre-production undulator, we modelled the effect of recessed magnets on the magnetic field. This modelling confirmed that recessed magnets could produce the same gap-dependent tapering we observed.

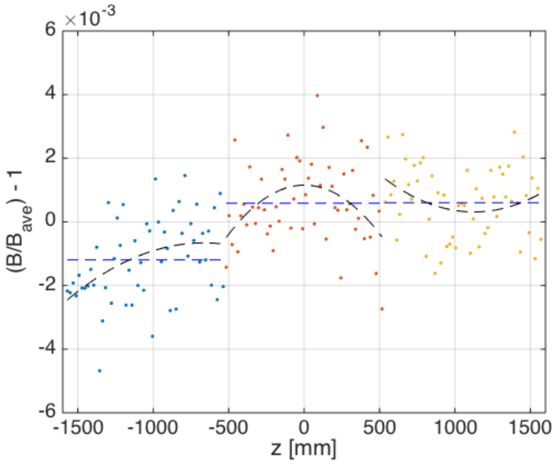

Figure 5: Peak fields on the preproduction SXR at 7.2 mm gap. The taper shrinks at 22 mm gap.

Following the experience with the pre-production undulator we changed the requirements such that the mean pole height must be 140 µm above the mean magnet height.

In the pre-production unit we also had an issue where non-magnetic shim stock was left underneath the magnet, and this resulted in the magnet sticking up above the poles. Therefore the requirement to check the height of every magnet was added to the procedure.

Magnet height data was taken on the first two production units. No magnets are sticking up above the poles, and the mean pole height to magnet height difference is maintained over the length of the strongback. The magnetic measurements needed to confirm that these requirements eliminate the observed field error at small gaps will take place over the course of the next few months.

MAGNET SPACING IMPACTS

The pole flexures give us height and cant adjustability but also make the pole longitudinal position more flexible. We decided that having the magnets directly touch the pole would result in undesirable hysteresis during the opening and closing of the gap due to friction between the moving pole and the stationary magnet. Thus, the design leaves 200 µm of air gap per half period, such that if the magnet is centrally placed, it would have a 100 µm air gap between it and the poles on either side of it.

There were no issues with magnet spacing on the prototype. However, each magnet slot on the prototype was filled by two 55 x 16.95 x 10.67 mm magnets while each magnet slot on the SXR is filled by one solid 56.5 x 63 x 11.5 mm magnet of the same material. Since they are thicker, wider, and much taller, the SXR magnets exert more force on each other during installation. Simulations showed that the maximum axial force on the SXR magnets during loading would be 281 N, which we considered high, and devised a plan to first load all the odd magnets and then load all the even magnets. This would result in a maximum axial force of 145 N.

When we measured the magnetic field of the pre-production SXR we discovered that the peak field strength of upward pointing poles was systematically weaker than downward pointing poles. Investigation into magnet-pole gaps using shims showed that the magnets were systematically positioned as shown in Fig. 6, which simulation showed would account for the observed magnet measurement. Indeed, when our technician moved all of the magnets to a more central location, the effect disappeared.

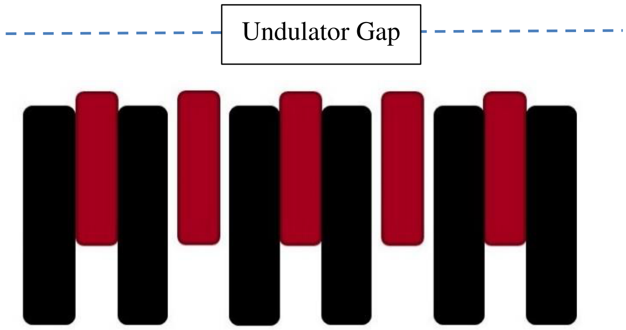

Figure 6: Magnets (longer, black) nearly touch the downward pointing poles (shorter, red) while having a large gap between them and the upward pointing poles.

We went back to the plan of loading magnets sequentially despite the higher forces. We added the step of putting a non-magnetic dummy magnet in the unfilled magnet slot to reduce the effects of pole flexibility.

The new method was used on the first 2 production SXRs and the systematic magnet positioning issue was resolved. The magnet positioning is now randomized.

ACKNOWLEDGMENT

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