SLIDE 2

The magnetic structure was changes significantly from for LCLS-II with period increased from 39mm to 56mm. The structure was optimized for maximum magnetic field and for minimum pole saturation. The pole adjustment mechanism was changed also. It is more like on HXR undulator. We have fabricated a short prototype with the new structures and tested it at SLAC MMF.

I’ll start my talk discussing the measurement set-up, following by requirements relevant to magnetic measurements and lessons learned.

Next, I will discuss the tests we did on the prototype:

First test was to check that the new design meets the PRD tolerances on magnetic field. We understand that the short prototype does not represent the full scale device. A full length undulator needed to satisfy requirements on K accuracy, phase errors and field integrals.

The second test was to measure shim signatures and to check if shimming options are sufficient for tuning. Also, the shim signatures could reveal if there is saturation in the poles.

The third test was to check if our measurement systems are accurate enough for higher fields, if we need to do any upgrades, modifications to our procedures.

And the last test was to study the cross-talk between undulator and phase shifter.

We would like to find the minimum distance at which the change in field integrals is insignificant.

We set the limit on the field integral change to 3G-cm.

Also, we wanted to get hands-on experience working with the new magnetic structure; to be prepared in advance for the pre-production prototype tuning, which could be the first undulator installed in the tunnel.

SLIDE 3

Measurement set-up.

Two 14 poles, 36cm long magnet structures were assembled and mechanically tested at LBNL.

At SLAC we attached the structures to a 1m long prototype frame, leftover from LCLS-II project, to make a short prototype of LCLS-HE undulator. The frame was in a good shape mechanically. Only motors and the motor controller were upgraded.

There are no gap encoders; the motor encoders’ offsets are set at 7.2mm gap with the use of a ceramic block. Accuracy of setting the gap with motor encoders was enough for the tests, which mostly required field integral measurements.

The prototype was placed next to the SXU measurement bench, as shown in the picture here. Magnet structures were aligned to each other and to the bench granite with the use of a laser tracker.

When we did the first measurements with Hall probe, there was a taper in the magnetic field along the beam axis. We corrected the taper by inserting shims in between the magnets’ keepers and supporting strongbacks.

For measurements we used the same equipment as for LCLS-II project: Sentron 2-D Hall probe to measure fields and we used a moving wire to measure field integrals. It is not a single wire but a coil with 150 turns. It improves the signal to noise ratio.

SLIDE 4

Here are the requirements. They are similar to LCLS-II tolerances. Tolerance on undulator parameter and field integral tolerances are relaxed. The last column shows the prototype measurement results. Because the device is short, not all tolerances could be satisfied. The tolerances, which could be satisfied, are met with a good margin. I’ll discuss the results in more details on the next slides.

SLIDE 5

Lessons learned from the LCLS-II experience.

SLIDE 6

The first measurements to evaluate the magnet structure design were the Hall probe measurements. Fields, measured at 7.2mm gap, are shown in the picture, Bx field on top, By field on the bottom. It looks like a nice short asymmetric undulator. What could be said? The K is 9.69 which is ~5% higher than needed.

The structures are assembled well. Small random Bx peaks indicate that there are no large magnetization errors in the magnets, the pole alignment is good, and the magnet sorting is good also, even for such a short device. The average undulator period for core poles is close to required.

This picture shows the average absolute field peaks vs. gap. Dashed line is the tolerance. At small gap the fields are above the tolerance.

SLIDE 6

Because the device is short, we couldn’t say much about the phase shake but it was small. The field roll-off, shown in the picture is in tolerance.

The second field integrals along the undulator are shown in the picture here. There are small jumps noticeable after each end section. The jumps come from the end sections/core misbalance because the structure is too short. This jumps agree with simulations done by LBNL. For the full scale device the misbalance should be much smaller. In any case, the total field integral is well below the tolerance.

SLIDE 7

This picture shows the long coil ready for measurements.

Since the device is short, only the first field integrals were measured.

Background field integrals were measured without prototype and then subtracted from all measurements.

Field integrals vs gap are shown in the pictures.

There is some waviness in fits, which comes from measurement errors, 3G-cm.

Normally, the By field integral should have the same shape as Bx. The small but sharp change in By field integral at ~ 9mm gap, we think, is due to magnetization errors and, possibly, pole saturation effects. We need to be prepared for tuning such integrals, to have shims with the same (opposite) shim signature.

SLIDE 8

Initially, we had 2 options for shimming, the same as for

LCLS-II SXUs and HXUs:

The first one is to move poles vertically. Parallel pole shift changes undulator gap and, therefore, the By dipole field. By rolling the poles we could create transverse field and normal quadrupole.

We made a tool based on capacitive sensors to control the pole shift, shown in the picture here. We scaled the old fixture up to fit on the new structure. All data will be saved in a data file.

The second option for tuning is to add extra magnetic material to the structure by inserting small, 3mm diameter or large, 8mm diameter slugs into dedicated holes in the magnet keeper. The slugs could be stacked together 2, 3 or 4. With slugs, the same field components could be created as with pole shift plus skew quadrupole.

We studied also the third option for tuning, ferromagnetic shims. With ferromagnetic shims we could create the same components as with slugs plus sextupole.

Different types of shims have different shim signatures and usually used in combinations to get the correct shim signature.

Ideal shim signature has the same gap dependence, the same shape, as a field integral to be tuned.

SLIDE 9

The shim signatures for the By field component are shown in the picture. They look as expected.

Also, in black on this picture is shown a shim signature for LCLS-II SXU undulator. There is a typical for SXUs ~15G-cm drop in shim strength below 8 mm gap. It is due to the pole saturation. We do not see anything like that on the prototype shim signatures, just measurement errors. We concluded that the pole saturation is small.

On the right picture the shim signatures for the combinations of two shims is shown. The ferromagnetic shim plus the pole shift give the signature much closer to required, with a bump around 10mm gap.

SLIDE 10

Here are shim signatures for other field components. Nothing special, except that the slugs, even the big ones, are very weak for these components at small gaps. The ferromagnetic shim signature have much stronger gap dependence as expected.

Having the ferromagnetic shims as an option for tuning is highly desirable.

More accurate measurements of the shim signatures for tuning will be done with the pre-production undulator.

SLIDE 11

We would like to use the ferromagnetic shims for tuning but there is a challenge. In initial design the recess between magnets and poles is 140µm. If installed as is the shim will protrude into the gap reducing it significantly. We wanted to make this recess bigger, 300µm at least. It would reduce the main field but by a small amount. To test it, we moved the poles up by 150µms. The poles’ adjustment range was big enough. It was a good practice for our technicians. They did an excellent job, which was confirmed by the CMM measurements. All poles were moved by equal amount but the first and the last poles, which we left as is because they have zero magnetic potential and their positions have no effect on field integrals.

The vertical field was reduced by ~0.5%, as expected, from 1.85T to 1.84T (still 4% higher than requirement). We think, 4 percent is a good margin to compensate for any deviation in magnetic properties of magnets and poles during the production.

No change in phase shake or field integrals.

Magnet/pole recess in the magnetic structure was increased from 0.140mm to 0.300mm. Here is the change request document. (LC-1006-3187\_HESXR\_DEV0011).

SLIDE 12

At the end of the test we tuned prototype field integrals ±20µTm by applying combinations of shims.

SLIDE 13

The pole adjustment worked fine for most of the poles and our technicians could do the pole adjustments very accurately.

There are a couple of challenges for tuning we encountered:

As shown in the picture of SXU undulator, there is no access to the side pole locking screws near the frame vertical supports. You could see it better in the picture in the center. The 2 side screws should be loosened before adjusting the pole and locked back again. But they are not accessible everywhere. It cuts off from tuning approximately 1/4 of the poles. The same issue is with the small slugs which are to be inserted from the side. It will be an issue for tuning phase errors. As a mitigation, we could use ferromagnetic shims or big slugs in those areas but it is not desirable. Another option is to make a fixture like we used for HXUs, shown on the picture, if we could make it fit into the small space. It has a hex tip and a knob connected with a tiny 90 degrees gear. It wouldn’t let us do the poles right next to the vertical supports but we could do the poles in compensation springs area, reducing the number of “un-tunable’ poles by a factor of 2.

The big slugs, if stacked together, make a quite big magnets which is hard to handle close to other magnets and steel poles in the gap. Also, they tend to flip-over in the holes. We would like to reduce the large slugs’ diameter and holes’ diameter in the keepers respectively and increase the height of the slugs at the same time to keep the amount of magnet material roughly the same.

We’re working together with LBNL to resolve these issues.

SLIDE 14

To meet the requirement on K, the undulator field needs to be measured reliably with high accuracy for the duration of the production run, more than a year. From our experience with other projects, we know that the Hall probe gain drifts continuously in time. During the LCLS-II production run we had the probe re-calibrated and our reference undulator re-measured at frequent intervals, usually after every 3-d or 4-th undulator tuned, to guarantee the consistency of the measurements. We’re planning to do the same for LCLS-HE.

For LCLS-HE, we’ll need to measure higher fields, as shown in the table. We need to calibrate our probe for even higher fields. This test was to check our calibration procedure and to make changes if needed.

There were two challenges related to higher field calibration.

First, the probe output is very non-linear at fields above 1.5T, as shown in the picture. We used to do the calibration measurements at discrete points and then fit the data with high order polynomials. Before, we needed the 10-th order polynomials, now for fields up to 1.9T the polynomials should be of 15-th order or higher to get reasonable fitting residuals. It looked a little bit risky for us to use polynomials of such high order. We switched to cubic splines.

The second challenge is that the calibration magnet saturates at higher field reducing the good field region. We have set the calibration magnet gap to the minimum to make the roll-off smaller and we modified the probe’s supports for better probe positioning, to have them on the same field.

We had the probe re-calibrated many times in one month timeframe for a test I’ll discuss on the next slide. The results are shown in the picture. The first calibration was subtracted from the all the other calibrations.

This picture shows that if we keep the same measurement procedure, re-calibrating the probe ones a month, the maximum error we’ll make will be 0.5G or less.

Before, it used to be 0.3G. The relative accuracy of probe calibration is about the same ~3\*10-5.

SLIDE 15

The measurement error consists of not only the calibration error, but of other errors, like probe alignment on the bench, errors in finding magnetic axis, the errors from the gap drift due to temperature change and cetera.

To estimate the measurement accuracy, or to estimate how repeatable we could measure the fields, we did a test which consisted of alternate Hall probe recalibrations and the prototype re-measurements.

The gap of the prototype was set to 7.3mm and was not changed during the test. Since we have no gap encoders, we expected the gap will drift for a few days under the magnetic field force. Also, the gap could change due to ambient temperature variations (±0.1C°).

The results of the test are shown in the picture as a relative change of undulator K w.r.t the first measurement in 10-4 units.

The vertical dashed lines show the dates of probe re-calibrations.

There is a clear drift in K during the first 3 days. So, we ignored the first 6 measurements. We estimated the Hall probe measurement accuracy from deviations from the linear fit as ±9∙10-5.

We conclude that the Hall probe measurement repeatability meets the LCLS-HE requirements (<1∙10-4).

SLIDE 16

We’ll calibrate the phase shifters without undulators. In the tunnel, the steel poles of an undulator will truncate the phase shifter fringe fields changing the field integrals. We would like to test how close we could place the phase shifter next to the undulator so that the field integrals change would be insignificant. We specified the limit on field integral change as 3G-cm.

The HE phase shifter prototype with a new magnet structure was mounted on a slide which could be moved along a rail. The gaps are set for maximum interference; to minimum gap for the undulator and to maximum operational gap for the phase shifter.

The distance between the phase shifter and the undulator was measured between the DS side of the last undulator pole and the US side of the first PS magnet.

Results of the measurements are shown in the pictures. A dotted line is a polynomial fit to the measurements. The fit line crosses the 3G-cm limit at 13cm distance between phase shifter and undulator.

In the tunnel, the undulator/phase shifter distance will be 14.4cm. From these measurements the change in field integral is expected be <2G-cm, which is below accuracy with which we measure the field integrals.

There is no change in Bx field integral for all distances. The cross-talk is insignificant.

The phase shifter design meets the cross-talk requirements.

SLIDE17

The magnetic structure design meets the PRD requirements.

Pole saturation is small.

Shim signatures were measured. After adding ferromagnetic shims, the field shimming options are sufficient for tuning the field integrals to tolerances.

Magnet/pole recess increased from 0.140mm to 0.300mm for ferromagnetic shim installation.

Hall probe measurements accuracy is below 10-4, meets the requirements on K measurements.

Undulator/phase shifter cross-talk starts at 13cm. No cross-talk is expected in the tunnel (at 14.4cm).

Next step is to measure, tune and calibrate the pre-production prototype. There should be no much difference from LCLS-II SXU undulators. We think, we’re ready.

The work will start in Q3 this year.

After tuning, we would like to measure the full final dataset to make sure all the requirements are met. Also, we will do the temperature and the beam pipe corrector calibrations.