REFINEMENT OF HALL SENSOR CALIBRATION WITH LONG COIL FOR UNDULATOR MEASUREMENT

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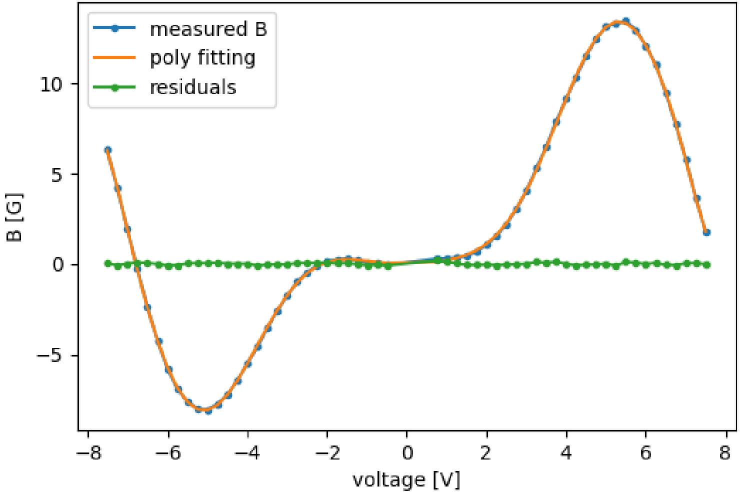
HALL PROBE CALIBRATION SYSTEM

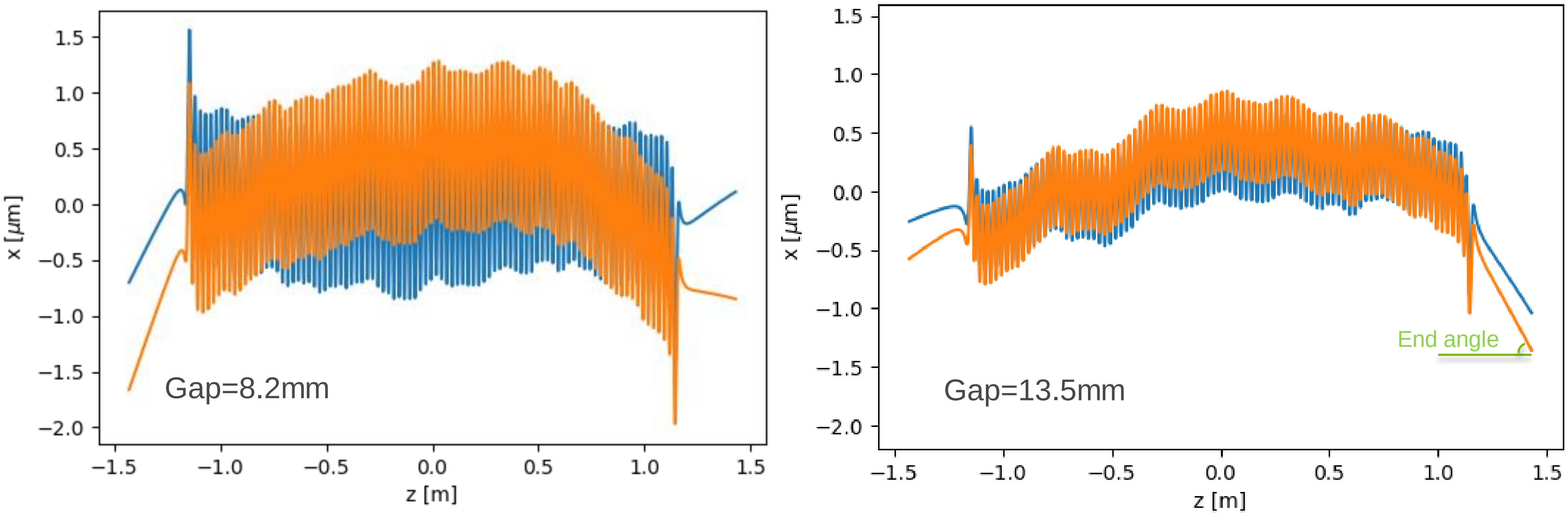
- Calibration of Hall sensors consists of placing the sensors into a reference magnetic field of variable intensity and recording the field intensity from a Nuclear Magnetic Resonance (NMR) meter and the output voltage from the sensors. The outcome is a Field (B) vs Voltage (V), i.e., a B-V relationship.

Standard (reference) dipole magnet used for Hall sensor calibration in the Magnetic Measurement lab (MM1) at the Advanced Photon Source (APS).



A typical B-V curve for Hall sensor calibration (the linear term is not shown). A polynomial fitting is applied to the curve and the resultant coefficients are used to reconstruct the magnetic field: $B = \sum c_n V^n$

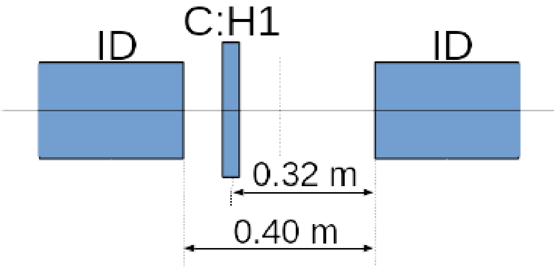
GAP-DEPENDENT FIELD INTEGRAL ERROR



Measured beam electron trajectories for a 25-mm-period planar undulator for the APS Upgrade at 6 GeV by two Hall probes at 8.2 mm gap (left) and 13.5 mm gap (right). Blue curve: Probe A, Orange curve: Probe B.

- A dipole-like field over the same z-range of the undulator causes the trajectory to bend differently.
  Thus the trajectory end angles are not well defined.
- The dipole-like field contributes ~60 G*cm of first field integral (J1y) at 8.2 mm gap and ~20 G*cm at 13.5 mm gap.

IMPACT – END ANGLES



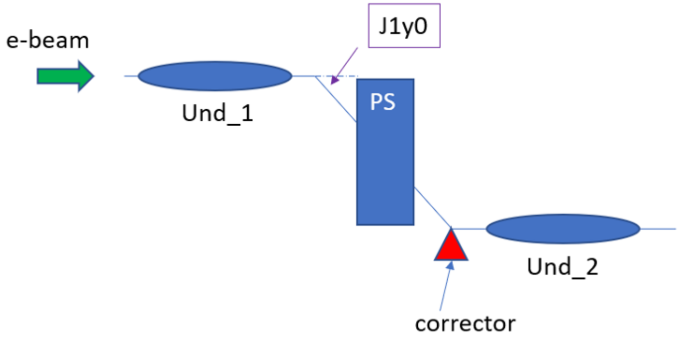
Schematic of the canted undulator section for the APS Upgrade (APSU) consisting of two insertion devices (IDs). The variation of end angles for each ID needs to be held within tight specifications so that the radiation beam spot remains stable while changing the undulator gaps (radiated photon energy).

Entrance/ exit angles	Experiment gap range (μm)	Usable gap range (μm)	Full gap range (μm)
Horizontal	±3.9	±5	±10
Vertical	±1.25	±2.5	±10

Entrance and Exit angle requirements for two independent (canted) IDs installed in a straight section of APSU.
1 μrad = 20 G*cm for 6 GeV electron beam

To tune the undulator end angles within specifications measurement of the end angles must be accurate!

IMPACT– PHASE MATCHING OF TWO UNDULATORS



$$
\begin{aligned}
PhaseInt &= \int_{z_1}^{z_2} J_1'(z)^2 \mathrm{d}z \\
&= \int_{z_1}^{z_2} (J_1(z) + J_{1,0})^2 \mathrm{d}z \\
&= \int_{z_1}^{z_2} J_1(z)^2 \mathrm{d}z + \int_{z_1}^{z_2} J_{1,0}^2 \mathrm{d}z + \int_{z_1}^{z_2} 2J_1(z)J_{1,0} \mathrm{d}z \\
&= \int_{z_1}^{z_2} J_1(z)^2 \mathrm{d}z + \int_{z_1}^{z_2} J_{1,0}^2 \mathrm{d}z + 2J_2J_{1,0}
\end{aligned}
$$

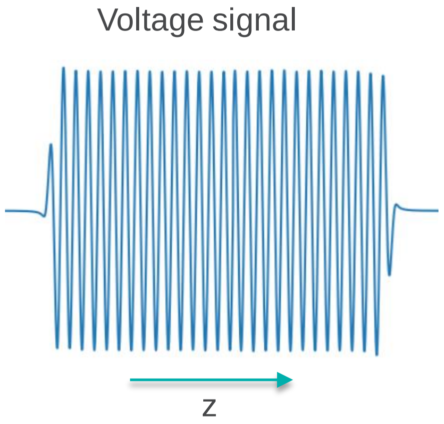
The layout of the APSU in-line section consists of two undulators, a corrector, and a phase shifter. The electron beam enters the phase shifter with an incident angle that is determined by the exit angle of the first undulator ($J_{1,0}$).

The electron beam enters the phase shifter with the angle $J_{1,0}$, which will cause an additional phase delay due to the cross term of $J_{1,0}$ and the phase shifter second field integral J_2.

The APSU phase shifter has a design value J_2 of 2500 G*cm^2. An end angle error of 20 G*cm will contribute an error of 3 degrees to the phase integral when two 25-mm period undulators are working at K=1.86.

To predict the phase shifter’s working condition correctly the undulator end angles need to be measured accurately.

GENERAL IDEA OF REFINING CALIBRATION

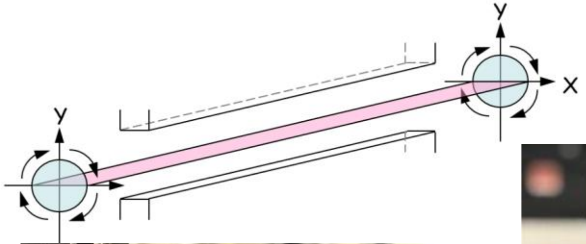


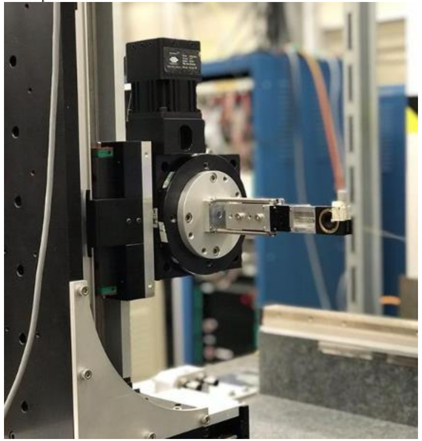
J1y by error in odd-numbered terms: $\int c'_{2n+1} V^{2n+1} \mathrm{d}z \sim 0$

J1y by error in even-numbered terms: $\int c'_{2n} V^{2n} \mathrm{d}z$

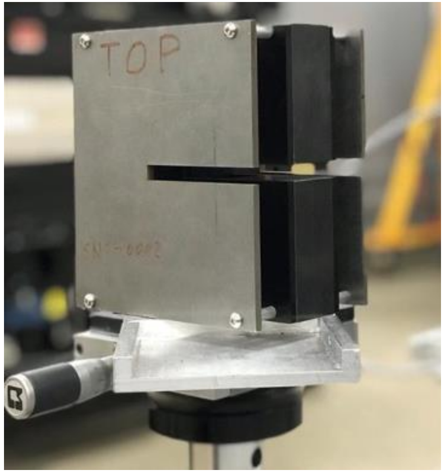
- Only the even-numbered terms for the Hall probe calibration coefficients contribute significantly when reconstructing the magnetic field from the voltage signal to obtain the J1y, and each term contributes differently at different gaps.
- The field integral can be obtained (relatively) accurately by rotating coil measurement, thus it is possible to correct the even-numbered terms based on rotating coil measurement.
- The trajectory shape is not sensitive to the error in the odd-numbered terms.

ROTATING COIL SYSTEM

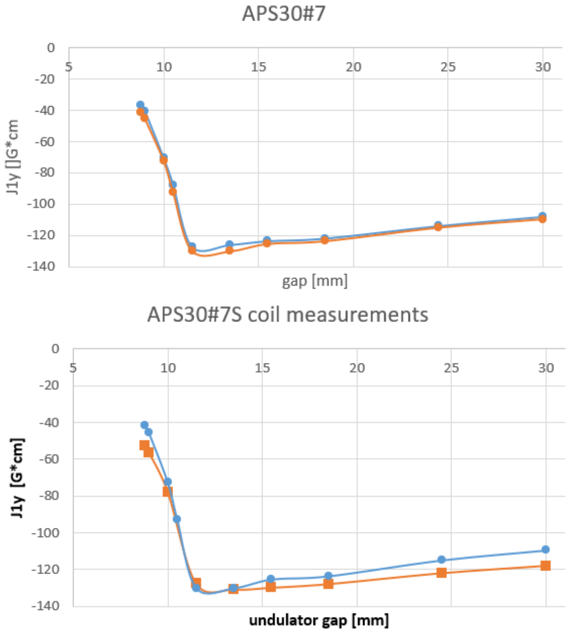




Top: Schematic of the rotating coil measurement system.
Bottom: Coil supporting structure in MM1.
The coil has one turn with a width of 3 mm.



Permanent magnet dipole used in MM1 for calibration.
The field integral is 2300 G*cm.



Top: Rotating coil repeatability on the same bench.
Bottom: Repeatability on two different benches.
(Blue: 3 m bench, Orange: 6m bench).

Each bench is equipped with a rotating coil system of the same design. Length=3m.

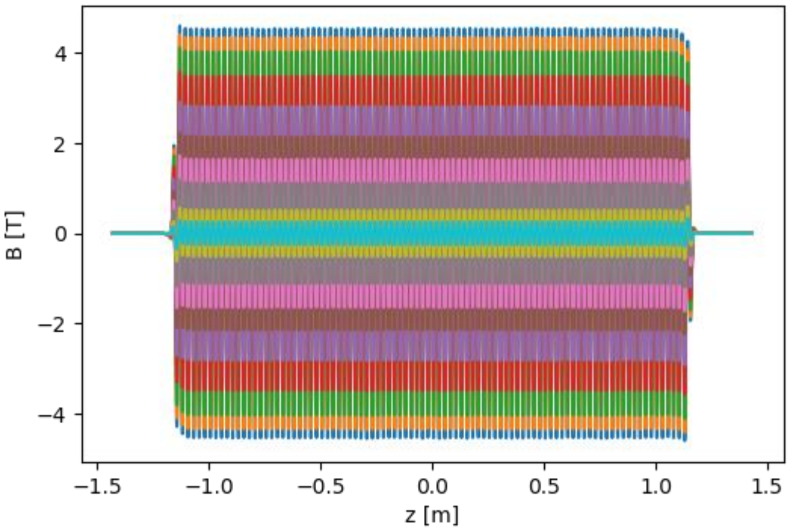
- Same-bench-repeatability: <5 G*cm
- Different-bench-repeatability: <10 G*cm

REFERENCE UNDULATOR AND HALL PROBE

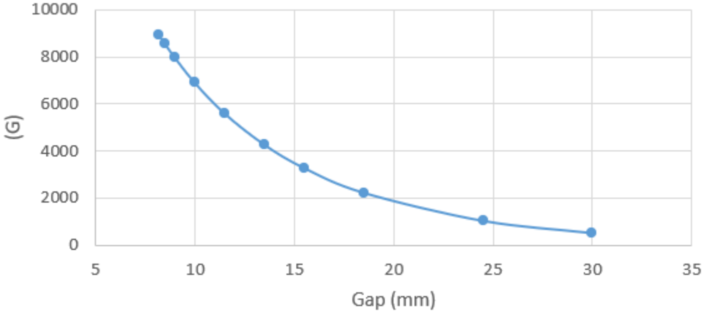
Photograph of the reference undulator APS25#4.
Configuration: Hybrid planar
Period length: 25 mm
Total length: 2.4 m

Photograph of the Senis 2-axis high-precision Hall sensor and transducer.
Sensitivity: 5V/T

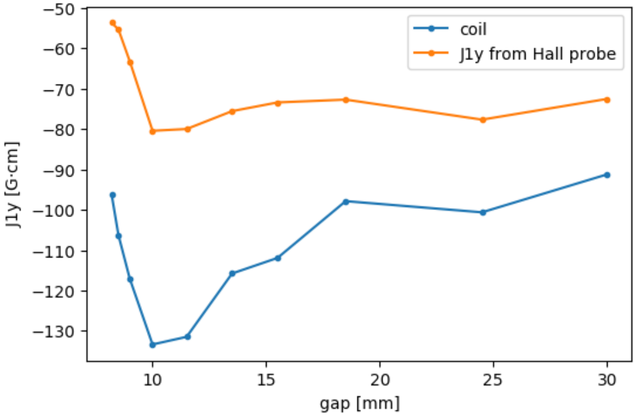
REFERENCE UNDULATOR MEASUREMENTS



Voltage signals of APS25#4 at different gaps ranging from 8.2 mm to 30 mm.
The Hall sensor scan range in z was set the same as the coil range.



Measured effective field vs. gap.



Measured first field integral from the rotating coil and the Hall probe.

HALL CALIBRATION REFINEMENT (1)

First obtain the gap-dependent “signature” of each even-numbered term.

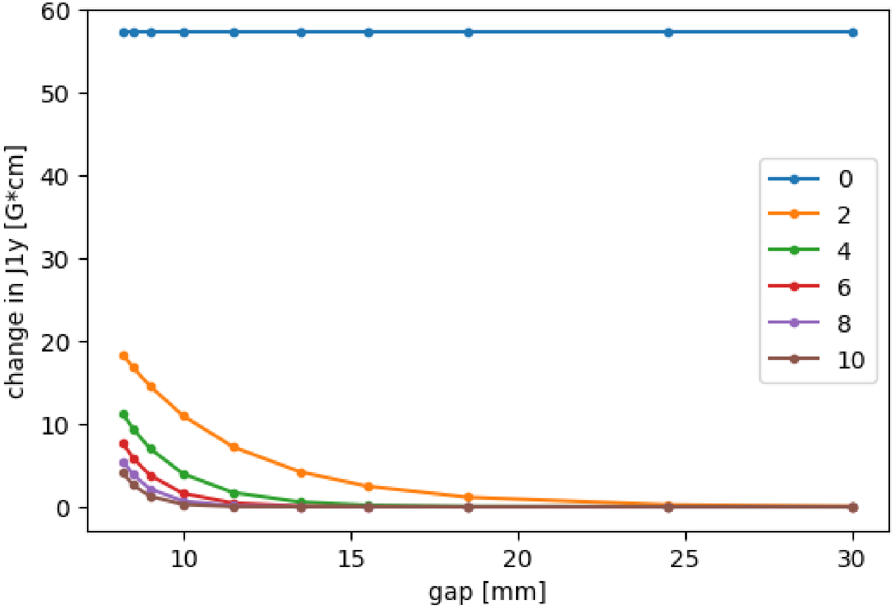
- Tweak one term by a small amount
- Re-generate the magnetic field profiles at all the gap and monitor the change in J1y.
- Repeat the above two process for the even terms to be refined to get the signatures $s_{2n}(gap)$ for them. n=0,1,2, …

We assume that the discrepancy in J1y between the Hall sensor and the rotating coil can be written as:

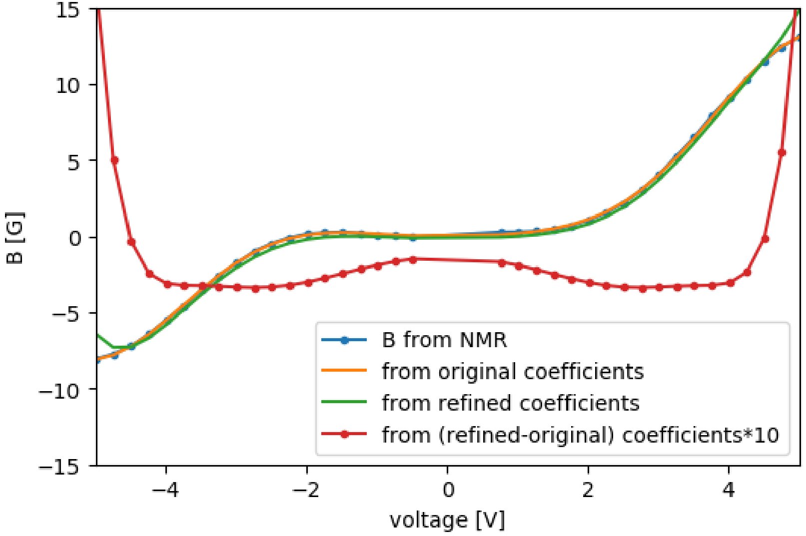
$$\sum c'_{2n} * s_{2n} = J1y_{coil} - J1y_{hall}$$

where c'_{2n} is the needed change in the 2n-th term.

The above equation can be solved by the Least Squares Method given that the number of the terms being refined is smaller than the number of the undulator gaps measured.

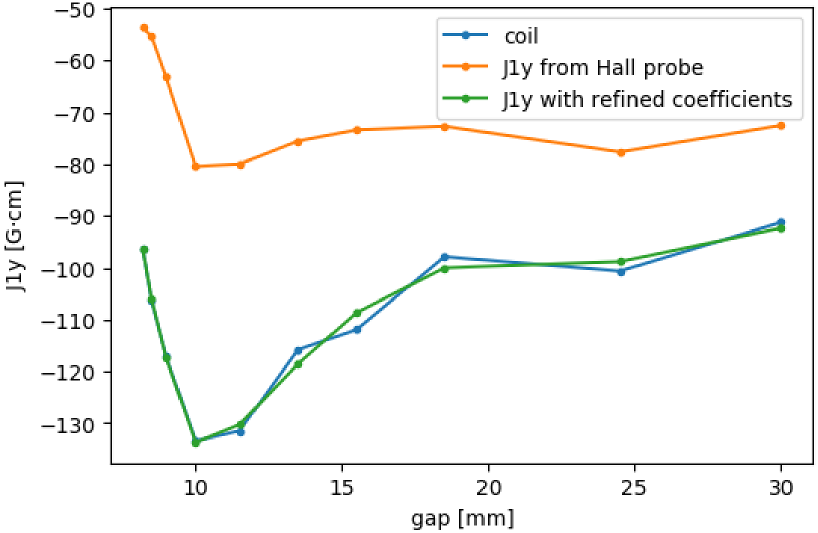


HALL CALIBRATION REFINEMENT (2)



B-V curve including the relative change by using refined coefficients (the change in red curve magnified by a factor of 10).

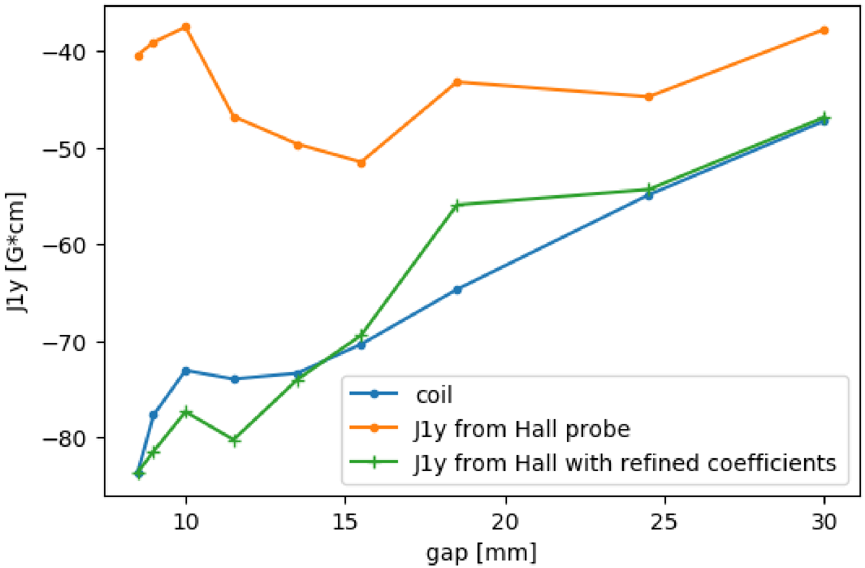
- The refined curve (green curve) does not converge beyond the maximum peak field of the reference undulator.



Comparisons of J1y from Hall probe measurements and coil measurements.

- Applying the refined Hall probe coefficients to the voltage data shows remarkable good agreement between the measurements.

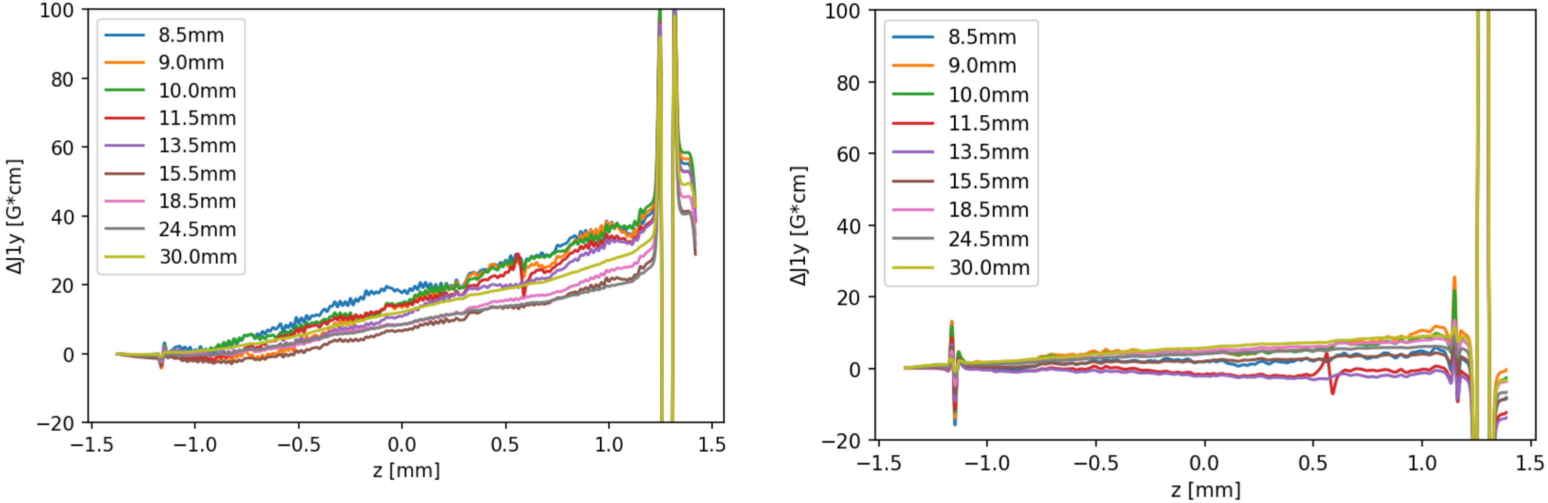
APPLICATION EXAMPLE #1



Comparison of first field integral measurements with the same Hall sensor w/ and w/o the refinement process.

- The undulator has a period of 21 mm and a total length of 2.4 m. The peak field at the minimum working gap of 8.5 mm is 0.75 T.
- The Hall probe measurements with refined coefficients agree well with the rotating coil measurements.

APPLICATION EXAMPLE #2



Differences in J1y measurements for an undulator on the 6-m bench and the 3-m bench.
The running first field integral $J1y(z') = \int_a^{z'} B_y(z)\mathrm{d}z$ is compared because there was interference from the phase shifter at the z+ end (first field integral not available). The running J1y(z) has been period-averaged. The 25mm-period 2.4m undulator has a peak field of 0.85T at a minimum working gap of 8.5mm.

Left panel: Only 3-m bench probe was refined.
Right panel: Probes on both benches were refined.

- For the two-bench comparison (right panel) the improvement after the refinement process is clearly seen.

SUMMARY

- We have developed and implemented a procedure to refine the Hall sensor calibration by using the first field integral of an undulator from a rotating coil measurement system as a reference.

- The application of this procedure has improved the accuracy of the Hall sensor measurements so that accurate measurements of trajectories including trajectory end angles are feasible.

- We have applied this procedure to both old and new hybrid permanent magnet undulators tuned to tight magnetic specifications for the APSU.

- This improved Hall probe calibration will benefit other multi-undulator applications such as those for Free Electron Lasers.