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MAGNETIC MEASUREMENT DEVELOPMENTS FOR UNDULATORS

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Abstract

FLASH2 is an extension of the present VUV-FEL facility at DESY. It includes a separate tunnel with a 12×2.5m=30m long planar hybrid undulator. The undulators have 31.4mm period length and 1T field at a minimum gap of 9mm.

The paper presents recent progress in the magnetic measurements of these undulators. Several specific details of the measurement tools will be discussed like peculiarities in the Hall probe calibration and noise, positioning accuracy and synchronization of voltage measurement with probes movement during scan, noise issues of various voltage integrators for stretched wire and search coil measurements.

HALL PROBE NOISE AND POSITIONING ACCURACY

The undulator with a period length of 31.4mm and 1T field amplitude has 0.2T/mm field gradients at the zero crossings. Having a noise level of the Hall probe of about 20 μT, the positioning accuracy should be better than 20μT / 0.2T/mm = 100nm in order not to add noticeable noise from the positioning jitter. This applies especially when magnetic field measurements are performed on-the-fly, continuously moving through the undulator with triggering of the Hall probe voltage readout by the position encoder. For shorter period in-vacuum undulators this problem could be more severe.

When scannig with a speed of 100mm/s, the trigger signal timing should be as accurate as 100nm / 100mm/s = 1us and any additional trigger synchronization logic inside the voltmeter, that adds delay or timing jitter, could significantly degrade measurement quality.

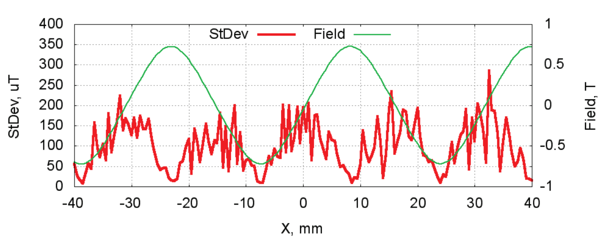

Figure 1: Reproducibility of an undulator field measurements; higher noise is found at locations of high field gradients.

Reproducibility of field measurements shows increase of noise up to 200μT at high field gradients (Fig. 1). Measurements without bench movements at field maximum and at zero crossing proved that this noise is not due to the trigger jitter during motion, but caused by intrinsic probe vibrations with an amplitude of about $200\mu T/0.2T/mm = 1\mu m$ and frequencies up to a few tens of Hz. The magnetic bench is moved on an air cushion, and the lever arm from the platform to the sensor is about 0.5m. For now, efforts to change cushion pressure setting and additional preloading of platform could change the noise spectrum, but the noise RMS value remained the same.

HALL PROBE CALIBRATION

Despite of good a reproducibility of the Hall probe calibration in a uniform field, measurements of a nonuniform undulator field show additional errors of the field integrals, in comparison to the stretched wire measurements.

The error in the first field integral was $150\mu Tm$ and $250Tmm^2$ for the second field integral, which corresponds to an average field error of $50\mu T$ over the scan range of 3m.

Also flipping the probe by 180 degrees, that should just change the sign of measured data, changes the field integral errors. In order to improve the calibration, tiny refinements to the even order coefficients of the calibration polynom were made using field integral data measured by stretched wire and Hall probe at different undulator gap settings. The normal and flipped Hall probe measurements at different gaps can be understood as a sampling of the Hall probe calibration polynomial at different field levels; the second field integral was used as it is very sensitive to any small field errors. This correction improves Hall probe calibration error down to a level of only few μT level (Fig. 2).

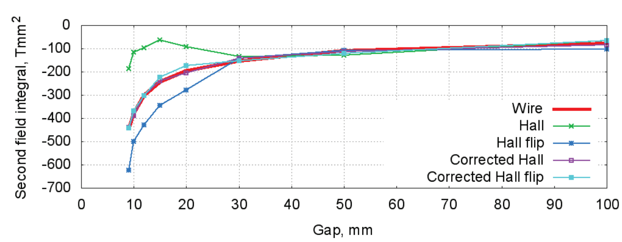

Figure 2: Second field integral gap dependence measured by stretched wire and Hall probe before and after correction.

SENSOR VOLUME AVERAGING

A non-zero sensor size causes some averaging of the measured field over the sensor volume. For a sinusoidal field of an undulator with period length λ_u, averaging over the sensor size d would make an error in the field amplitude of $\epsilon = 1 - \frac{1}{d}\int_{-d/2}^{d/2} cos(\frac{2\pi x}{\lambda_u})dx = 1 - \frac{\lambda_u}{\pi d} sin(\frac{\pi d}{\lambda_u})$. For 32mm period length and 2mm coil size, the error is $\epsilon = 6 \cdot 10^{-3}$, for a Hall probe size of 0.1mm $\epsilon = 1.6 \cdot 10^{-5}$. When the sensor size is known, it is possible to recalculate what was the field value before averaging by the sensor size. For non-uniformity along other coordinates, the vertical $cosh(y)$ field dependence and transverse field decay could be compensated in the same way. A vertical non-uniformity increases

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the measured value, while a longitudinal and transverse decreases it. Using a parabolic approximation of the transverse field dependence $B(x) = ax^2$, an amplitude compensation factor can be calculated as $\epsilon = \frac{1}{d}\int_{-d/2}^{d/2} ax^2 dx = \frac{a}{24d^2}$.

In order to test the accuracy of the search coil measurements, the same undulator was measured with a Hall probe and a search coil. Both sensors were calibrated by an NMR. After applying all the correction factors for the coil size averaging, the difference between Hall probe and coil measurements was below $5 \cdot 10^{-5}$, which is comparable with the absolute accuracy of the Hall probe and coil area calibration.

VOLTAGE INTEGRATOR NOISE

For long-time measurements with search coils, the low frequency noise of a voltmeter is a limiting factor. Also, this property is usually poorly described in the device specification as a single number of RMS noise at low frequency in a bandwidth of 0.1 to 10Hz. Such a number could hardly be used to estimate the noise level when the integration time is in the range of hundreds of seconds.

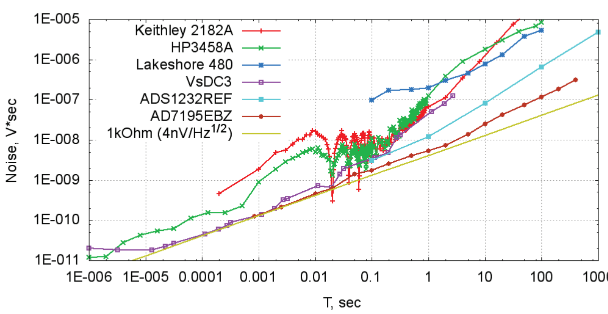

Figure 3: Voltage integrator noise level vs integration time.

In order to compare noise level of different voltmeters, the reproducibility of the voltage integral for different integration time was measured with shorted inputs (Fig. 3).

Digital multimeter HP3458A and Keithley 2182A nanovoltmeter show a poor power supply rejection rate, but at integration times corresponding to multiples of the 20ms power line cycle, they show a good noise performance. However, with increasing of the integration time to seconds, the low frequency (1/f) noise is predominant and significantly increases the noise level. Although the Lakeshore 480 hash a relatively high noise at short integration times, it could still be used as a preamplifier with analogue integration at longer integration times above a few seconds; in front of HP3458A it can reduce the noise by a factor of 2~3.

VsDC3 (Volt*second to Digital Converter) [2] has been designed at BINP for pulsed magnetic field measurements at microsecond time scale. Nevertheless, this voltmeter shows a reasonable noise level also at longer integration times.

Low frequency integrated sigma delta ADCs with a built-in preamplifier (AD7195EBZ evaluation board) shows an outstanding low frequency noise performance; it has nearly the same noise level as thermal noise of a 1kOhm resistor, which is proportional to square root of bandwidth, even at high integration times and is therfore well suited for long time measurements.

EARTH FIELD CORRECTION COIL

Each FLASH2 undulator has an air correction coil with two turns and a size of 35x2500mm embedded in the vacuum chamber. They were implemented to compensate ambient magnetic fields, which could be concentrated by undulator iron poles, and therefore depend on undulator gap setting. The same coil could be used for the field integral measurements. The integral of the voltage, induced in the coil during gap movement, is proportional to the undulator's 1st field integral. It is averaged transversely over the coil width of 35mm and hence differs from the field integral value on beam axis obtained by stretched wire; nevertheless changes of field integral caused by radiation damage could be measured with such a coil directly in the tunnel without moving undulator to the lab.

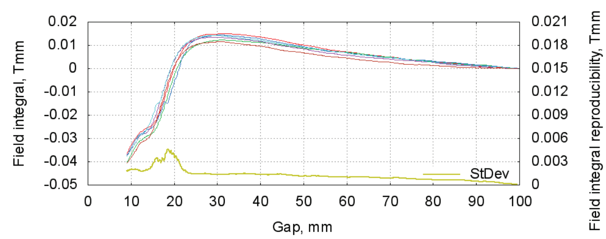

Figure 4: First field integral as function of gap and its' reproducibility, measured with the earth field correction coil and AD7195EBZ voltmeter in the FLASH2 tunnel.

It takes ~100 seconds to completely open or close the undulator gap. At such a long integration time, the noise level of AD7195 ADC is 100nV*sec (Fig. 3), but with the coil width of 35mm times 2 turns, this voltage integral noise corresponds to 1.5 μTm field integral noise (Fig. 4). The increase of noise at closed gap is due to poor synchronization between gap motion and voltage readout at that stage of the measurement setup; when going below 12mm gap, movement speed is automatically decreased for safety reasons.

STRETCHED WIRE MEASUREMENTS

Measurements of the field integrals by a stretched wire probe are performed by integrating the voltage, induced during the motion of the stretched wire that forms a single loop coil. One way of operation is to start integration before movement, and to stop after the movement has finished plus some delay to settle wire vibrations. The integral of induced voltage is equal to the total magnetic flux change, or first field integral times the movement step size.

When moving with constant speed, the induced voltage is proportional to the first field integral $U(t) = -d\Phi/dt = BL \cdot dx/dt$, or $I_1(x) = U(x)/v$. Comparing to step measurements of vertical first field integral, a measurement on-the-fly reduces the measurement time from 100 sec to about 10 sec, and the noise level by a factor of 4, down to $4\mu Tm$.

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However, such wire movement allows to measure the horizontal dependence of the vertical field integral, or the vertical dependence of the horizontal field integral, when the scan direction is perpendicular to the measured field component. In order to measure the horizontal dependence of the horizontal field, two scans are required with different vertical offsets $\pm d/2$. The voltage difference of these two scans is equivalent to a scan by a single loop horizontal coil with a width of d. To measure second field integrals, only one side of stretched wire should be shifted during scans, thus forming a triangular coil. By subtracting scans with different wire position offsets, it is possible to form various virtual coils of any shape with a single stretched wire.

This method has, however, also some drawbacks. It is required to integrate the measured voltage difference, as such virtual coils measure field changes but not the absolute field. The integration time increases to about ten seconds for a $\pm 40mm$ scan and requires a voltage integrator with an extremely low level of offsets drifts and low frequency noise. Two measurements are required; therefore the noise level of the difference of measurements is $\sqrt{2}$ higher. The absolute field integral level should be measured additionally at one or few points as the scan with the coil measures field level changes relative to the starting point.

MECHANICAL MEASUREMENTS AND ALIGNMENT OF THE UNDULATORS

In the magnetic measurement lab, the undulator magnetic axis is aligned parallel to the magnetic measurement bench. For proper transfer of the alignment into the tunnel, several mechanical reference marks on the undulator support structure are measured by a laser tracker.

After magnetic tuning by pole height adjustment, the real gap could be different for different poles. In order to control the real mechanical gap and check if some poles are shifted too much and thus limit the minimum gap, the pole height is measured additionally by a touch probe. The touch probe was mounted to the magnetic measurement bench instead of the Hall probe, and touching of the pole surface during vertical movement was triggering the position encoder of the linear stage. Absolute measurement accuracy is about $50\mu m$. To match the laser tracker measurement of the reference marks on the support structure with the touch probe measurements of the pole surface, special reference marks were additionally mounted at the magnet girder ends and measured with both laser tracker and touch probe.

In order to improve the mechanical measurements of the pole surface, an inductive sensor was tested: A coil with 100 turns and 1mm diameter is connected in parallel with a 100pF capacitor to the inductance-to-digital converter LDC1000EVM [3]. The LDC1000 measures the resonant frequency and losses in the coil. Coil inductance and losses, caused by eddy currents, depend on the distance between coil and conductive pole surface. The nonlinear dependence of losses versus distance can be calibrated once; then the sensor could be used to measure the height of each pole. The resolution of the LDC1000 is 16/24 bits and the typical noise level converted to distance is in the micrometer range with a readout rate of kHz. Also, such sensor allows to measure the pole height continuously moving along the undulator, which reduces the measurement time from hours for a touch probe down to a few minutes.

MAGNETIC TUNING OF UNDULATORS

The magnet structure of the FLASH2 undulators allows to adjust each pole in height and tilt. As poles of top and bottom girders are tuned independently, there are 4 configurations of pole movement: top and bottom poles shift in opposite direction to change the gap locally (vertical field); poles tilt in same direction (horizontal field); poles tilt in opposite direction (vertical quadrupole); poles shift in same direction (horizontal quadrupole).

A linear combination of these 4 adjustments at each pole could be used to tune the phase error and trajectory (horizontal and vertical) on axis as well as the local horizontal and vertical field integral gradients (quadrupoles) along the undulator. For trajectory adjustment, the Ramer-Douglas-Peucker algorithm is used for a piecewise linear approximation of the trajectory to find the optimal positions and amplitudes of the corrections. The phase error is tuned by minimizing the local K-value scatter. Local K is calculated from the phase error and is proportional to phase error derivative. Changes of local K by pole movements are somewhat localized to the pole that was adjusted. This is in contrast to the phase error where a single pole movement could create phase error distortions along all the structure because of trajectory changes. It is therefore much simpler to find the amount of pole adjustment required to correct the local K error and make it equal for all the poles which would also mean a zero phase error between each pole pair.

Using such an approach, only a single iteration of pole tuning was required to tune phase error and trajectory far below the required specification values. Tuning results are: trajectory standard deviation along the structure below $6Tmm^2$ for all gap settings; phase error below 1 degree RMS at minimum gap and below 2 degrees for all gap settings. Correction of quadrupoles along the structure greatly reduced the amount of magnets in magic finger correctors installed from both sides of the device to correct residual multipoles [4].

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