TEMPERATURE EFFECTS OF THE FLASH2 UNDULATORS

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Abstract

FELs are very sensitive to small changes in the resonance condition of the emitted radiation. As a consequence, permanent magnet undulators in FELs usually require extensive temperature control in order to assure stable operation conditions. In principle, the temperature dependence of permanent magnet material is well known but more things need to be considered like different thermal expansion of various mechanical parts or thermally induced deformation which do not only affect the K parameter but also the field quality. We have performed temperature dependent magnetic measurements in a range from 19 to 28 degrees Celsius and have analyzed the magnetic performance of the undulator. The results of this case study can be transferred to all FLASH2 undulators and shall allow for a simple temperature dependent gap correction in order to make the spectral properties insensitive to temperature changes of the insertion devices.

MAGNET MATERIAL REMANENCE

The temperature coefficient for the remanent magnetization of the magnet material VACODYM 776AP used for the FLASH2 undulators is -1100ppm/K [1]. For determining the effects of changes in the remanence on the magnetic field amplitude in a complex structure like a hybrid undulator, also the geometry and the saturation of the poles have to be taken into account.

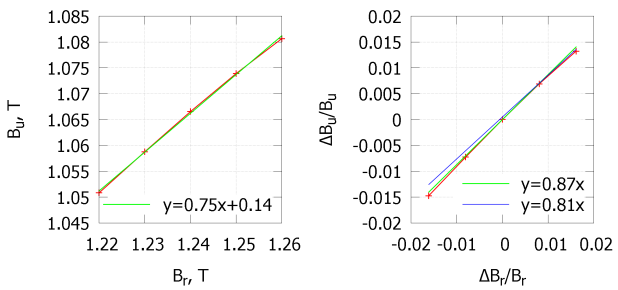

Figure 1: Calculated undulator magnetic field amplitude B_u versus magnet material remanence B_r (left) and $\Delta B_u/B_u$ versus $\Delta B_r/B_r$ normalized for B_r = 1.24...1.26T (right).

The dependence of the magnetic field B_u on the remanence of the magnet material B_r was calculated using Radia [2]. For the FLASH2 pole and magnet geometry, it can be described as: $B_u(B_r) = 0.75 \cdot B_r + 0.14T$ (Fig. 1). Therefore the expected relative change in magnetic field $\Delta B_u/B_u$ due to the temperature-induced change in the remanent magnetization B_r, normalized for B_r = 1.24..1.26T, is $\Delta B_u/B_u$ = -1100ppm/K · 0.87..0.81 = -960..-890ppm/K.

MAGNETIC MEASUREMENTS

Recently temperature effects have also been studied for XFEL undulators [3]. For the FLASH2 undulators, magnetic field maps were measured with different methods for crosschecking that the temperature dependence of the field sensors is properly compensated. The field was measured by a Hall probe, a pick-up coil and a stretched wire. The Hall probe and coil gain were calibrated by an NMR magnetometer in a 0.4T permanent magnet at each temperature change. This single point calibration was used for the Hall probe as mainly its gain and offset change with temperature, and changes of a higher order nonlinearity could be neglected. For the coil, the gain of the whole measurement system was calibrated, not just the coil area, as the coil and the integrator input resistances are also temperature dependent.

The alignment of the bench scan axis with respect to undulator magnetic axis was performed at each temperature change by magnetic measurements, in order to compensate probe displacement caused by thermal expansion of the undulator and the measurement bench.

In contrast to the Hall probe which has a small sensitive area with a width of 100μm, the coil measures a field which is averaged over its size of 3mm. For a sinusoidal magnetic field of an undulator with a period of 31.4mm, such an averaging reduces the measured field amplitude by up to 1% [4]. This gain error for the sensitivity of the coil would be the same for different temperatures, and the relative temperature dependence of the field amplitude could still be measured with a such sensor even without any gain compensation.

The stretched wire for the field integral measurements was installed transversely to the magnet structure, instead of the usual orientation along the undulator. This way, by moving the wire along the magnet structure, it measures the vertical field, averaged transversely over the whole pole width. Therefore the measured field could not be compared directly to the Hall probe and coil measurements on the beam axis. However, the temperature dependence of the average field should be the same as the temperature dependence of the field on beam axis. Also, only a small part of the magnet structure could be measured due to the limited range the moving stages of 100mm, covering only few undulator periods. The stretched wire setup was not calibrated. With 1mm wire step size, its gain is defined by the mechanical accuracy and temperature stability of the linear stages.

The measured temperature dependence for the magnetic field amplitude shows a linear behaviour with a temperature coefficient of -885±3ppm/K (Fig. 2). The 3 different measurement methods obtain this value in almost perfect agreement. The measured value compares very well to the calculated value of the B_r-induced temperature dependence. This indicates that other effects like thermal expansion of the support structure should be smaller than 80ppm/K.

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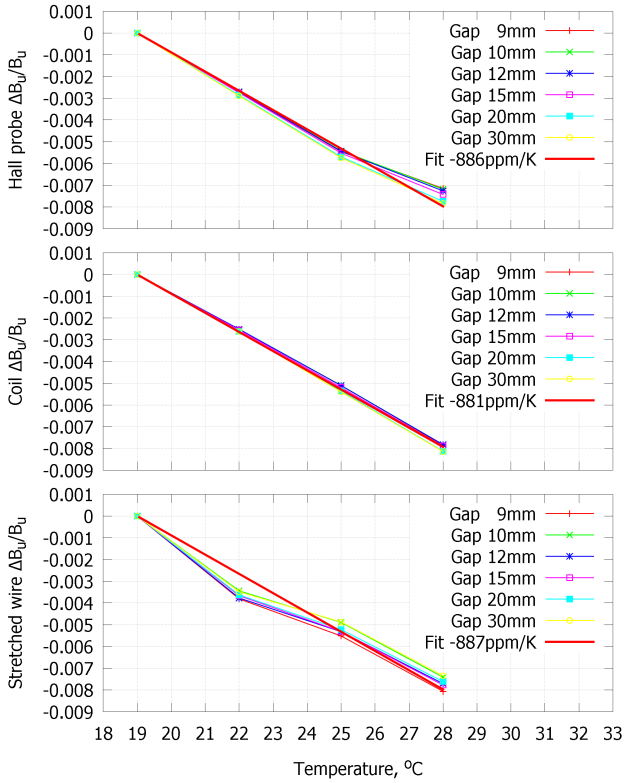

Figure 2: Measured undulator magnetic field amplitude vs temperature for different gap settings, measured with the Hall probe (top), coil (middle), and stretched wire (bottom), normalized to the field amplitude at 19°C. The measured temperature coefficient is -885ppm/K with excellent agreement between the three different measurement methods.

UNDULATOR GAP

The time-dependence of several sensor readings during the change of the ambient temperature was studied in order to reveal the time constants for the thermal behavior of different components. In this case, the readings of the temperature sensors at the magnet girders, the air temperature and the readings of the motor's rotary encoders have been monitored. Since the control system uses the additional linear encoders mounted on the magnet girders as a feedback for position control to maintain a constant magnetic gap, the changes of the rotary encoder readings at the motor axes reflect the thermal behavior of the support structure.

Figures 3 and 4 show that the readings of the rotary encoders follow the air temperature while the actual girder temperature adapts to the ambient conditions with a much longer time constant of about 10 hours. This behaviour can be explained by the fact that the caliper arms for the encoder systems have 25 times less mass than the magnet girders and a surface to volume ratio which is approximately 2.5 times higher. As pointed out clearly in Fig. 4, they adapt much faster to changes of the ambient temperature and cause the control system to correct for their length variation long before the actual gap has also adapted to the temperature changes.

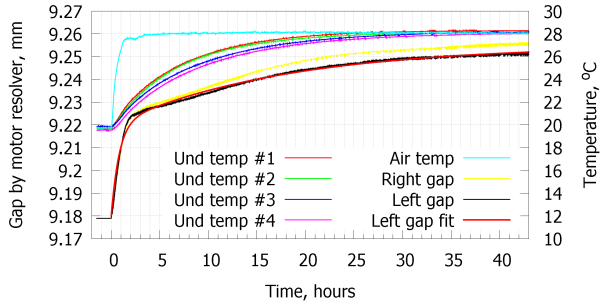

Figure 3: Motor rotary encoder reading and undulator temperature settling after a step change from 19.7°C to 28.1°C. The undulator temperature is measured by four Pt100 temperature sensors placed on the magnet girders. There are two processes, a fast change because of the encoder caliper arm expansion, which almost follows the air temperature change during the first hour, and then a slow temperature settling of the massive girders and the support structure.

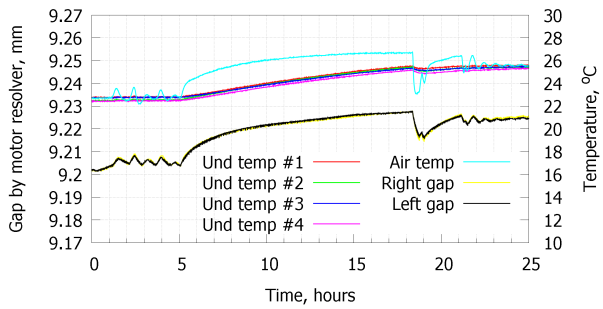

Figure 4: Motor rotary encoder reading during temperature changes. The temperature oscillations and instability are due to a single event failure of the temperature stabilization. This is a good illustration of the fast temperature response of the linear encoders compared to the undulator temperature.

Fitting the gap correction over time (Fig. 3) with

$$g(t) = g_0 + a_0(1 - e^{-t/t_0}) + a_1(1 - e^{-t/t_1})$$

provides $g_0 = 9.18mm$, $a_0 = 40\mu m$, $t_0 = 0.8h$, $a_1 = 35\mu m$, $t_1 = 10.7h$. A total gap change of 40+35=75μm per 8.4K corresponds to 9μm/K gap correction by linear encoders.

UNDULATOR SUPPORT STRUCTURE

The distance between the bearings for upper and lower spindles at the support is 1360mm (Fig. 5). It is made of steel type S235JR with a thermal expansion coefficient of 12ppm/K. The spindles themselves are made from a high-grade steel with similar thermal expansion coefficient and an effective length of 368mm each at a gap of 9mm. Therefore the girder fixation points have a thermal expansion coefficient of 1360mm · 12ppm/K - 736mm · 12ppm/K = 7.5μm/K. The linear encoder caliper arms are made from aluminum with an expansion coefficient of 25ppm/K and a length of 625mm; the related thermal expansion is -625mm · 25ppm/K = -15.6μm/K. Therefore the linear encoders should measure

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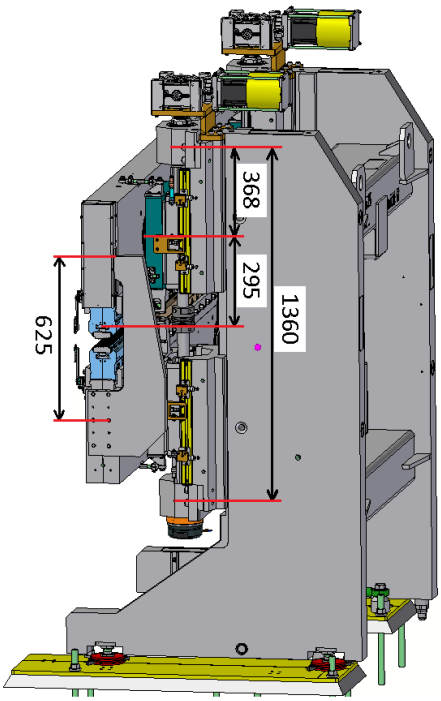

Figure 5: Undulator support structure with the dimensions of relevant parts in mm.

and compensate 7.5 - 15.6 = -8.1μm/K. Which is in a good agreement with the measured value of 9μm/K (Fig. 3) of the correction by control the system with opposite sign.

With a closed loop feedback for the undulator gap by linear encoders, the thermal expansion of the support structure does not affect the actual gap setting, as it is measured and controlled directly by linear encoders. Both the encoder caliper arms and the magnet girders are made of aluminum. Thus their thermal expansions almost fully compensate each other. Only the air gap between poles is not compensated. It correspondes to an effective length of about 30mm of aluminum with the thermal expansion coefficient of 25ppm/K providing 30mm · 25ppm/K = 0.75μm/K undulator gap temperature dependence. For the minimum undulator gap of 9mm and 1T field, an increase in gap of 1μm would result in a magnetic field change of -100μT. The thermal expansion of the undulator gap of 0.75μm/K corresponds to a magnetic field change of -75ppm/K.

UNDULATOR PERIOD

From the measured magnetic field maps it is possible to extract longitudinal positions of the magnetic field maxima. By calculating the average difference between them, it is possible to find the temperature changes of the undulator period. The measured value is +18ppm/K. Its sign is opposite to the magnetic field amplitude temperature dependence, but being 50 times smaller it can not compensate the latter in the emitted wavelength or undulator K parameter, which is a product of undulator period and field amplitude.

UNDULATOR AXIS VERTICAL OFFSET

The vertical cosh(y) dependence of the undulator's magnetic field could be approximated by a parabola with a 2^{nd} order coefficient of 2.57%/mm^2 at a gap of 10mm. With a beam height of 1.4m and a thermal expansion coefficient of 12ppm/K for the steel support structure, the undulator magnetic axis vertically drifts by 17μm/K. Therefore an on-axis field change of +7ppm/K^2 is expected. Due to its parabolic dependence it should be considered in case of temperature changes above a few degrees.

The measured mechanical offset drift of the undulator magnetic axis is 11μm/K, which is smaller than calculated for the undulator support structure, however the granite measurement bench also has its own temperature expansion that partly compensates the measured thermal drift of the undulator's magnetic axis in these measurements. In the tunnel, the vertical drift of the undulator's magnetic axis relative to the beam position should be considered.

CONCLUSION

In order to apply gap corrections to compensate temperature changes, several effects should be considered:

The temperature dependence of the undulator gap, which includes two parts: the thermal expansion of the linear encoders' caliper arms, which should be corrected based on air temperature or additional temperature sensors on the linear encoders; and the thermal expansion of the girders and support structure with a time constant of about 10 hours.

The temperature dependence of the magnetic field amplitude due to the remanence change of the magnet material, which should be compensated based on the temperature of the undulator girders.

With the known temperature dependence of the magnetic field and an exponential approximation for the field amplitude versus gap behavior, the required correction for a given gap value and temperature can be calculated.

Operation without linear encoders, using only motor encoders, requires not only a gap correction of the support structure deformation under magnetic forces, but also a compensation of the support structure's thermal expansion.

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