XFEL ACTIVITIES AT MSL: UNDULATOR TEMPERATURE COMPENSATION AND QUADRUPOLE FIDUCIALIZATION

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Abstract

Fundamental wavelength and phase-matching conditions in the XFEL undulator can be maintained during temperature changes with undulator gap adjustment in a temperature compensation scheme. Evaluation of a high-precision temperature measurement system suitable for the compensation scheme is presented together with a brief overview of an upgraded rotating coil system for fiducialization and characterization of the XFEL quadrupole magnets.

INTRODUCTION

The Manne Siegbahn Laboratory at Stockholm University is currently involved in two separate projects at the European XFEL. The first concerns the fiducialization and characterization of the quadrupole magnets in the undulator sections. These magnets are situated after each of the 5 m long undulator segments that build the over 100 m long undulators. The quadrupole magnets must be aligned to a straight line with accuracy of 2 μm and this will be achieved with the beam based alignment procedure which requires initial optical alignment with accuracy of 50 to 100 μm. A recently upgraded rotating coil system measures the magnetic centre stability during magnet excitation, magnet gradient and field error components. In connection, a coordinate measuring machine is used to fiducialize the quadrupole magnetic centre to better than 50 μm.

The second project concerns high precision measurements of the undulator temperature. The SASE radiation intensity depends strongly on the undulator period and the magnetic field strength, which are both sensitive to temperature. Instead of keeping the temperature within 0.1 degrees along the undulator tunnel, a temperature compensation scheme can be applied. Here, a change in temperature initiates adjustment of the undulator gap to compensate for changes in magnetic field. A system for undulator segment temperature measurement, with resolution of 0.03 degrees, necessary for the compensation scheme, has been tested and evaluated.

QUADRUPOLE MEASUREMENTS

The experimental setup for the fiducialization and characterization of the quadrupole magnets consists of a rotating coil system and a coordinate measuring machine. Rotating coils are widely used to characterize the magnetic field in accelerator magnets [1]. Here it is used to measure the distance from the rotational axis to the symmetry axis of the quadrupole magnet. The coordinate measuring machine is then used to measure the distance from the rotational axis to tooling balls on the magnet. This setup has been presented before together with measurements on quadrupole magnets made from different soft magnetic materials, the magnetic centre stability as function of magnet excitation and investigation of the accuracy of the fiducialization procedure [2, 3, 4, 5].

A new setup is currently being built to improve the accuracy of, in particular, the measurement of the magnetic field strength and multipole field errors. The coils are positioned in an epoxy rod positioned in metal shafts supported by ball bearings. For more controlled rotation and to minimize the sag the epoxy rod is now supported on both sides. The rod rotates with approximately 1 Hz using a stepper motor. The signals from the coils go through a mercury wetted slip ring, and are amplified before registered by a DAQ card in a computer. The new DAQ card is faster and with higher resolution (16 bit, 200kHz sampling rate per channel) than the original one. The perhaps most significant improvement is that prototypes of printed circuit board coils have replaced the old coils wound by hand. The dimensions of the circuit boards are $2 \times 12.8 \times 200$ mm. The first prototype has two coils side by side with 54 turns on nine layers with an average diameter of 3 mm. There is also a prototype of a compensated coil [6] that suppresses the signal from the dominant quadrupole signal when higher order field components are studied.

The new rotating coil setup will be used to fiducialize and characterize the in total 126 undulator quadrupoles magnets of the XFEL as they come in production in early 2011.

UNDULATOR TEMPERATURE

Temperature stability of the undulator system is of vital importance for maintaining the wavelength and phase-matching conditions, not only within an undulator segment but along the entire length of the undulator. Even a change in temperature of less than a degree, from one end of the undulator to the other, influences the radiation power significantly. However, this degradation in power, caused by change in the magnetic field strength from the permanent magnet material in the undulators, can be compensated for. Calculations and simulations have shown that if the temperatures of the XFEL undulators are monitored with suf-

* This project was performed within the framework of the Stockholm-Uppsala Centre for Free Electron Laser Research. For more information, please visit: http://www.frielektronlaser.se.

ficiently high precision and accuracy, a temperature compensation scheme can be applied to the undulators instead of having strict control of the ambient temperature [7].

In the proposed compensation scheme, the temperature is measured for all undulators. If the temperature increases or decreases above or below a certain threshold value, the undulator gap is changed to compensate for the change of magnetic flux and the ensuing change of undulator K value, caused by the change in temperature. Thereby the output power is retained. The threshold value for performing a change of the undulator gap is estimated to be between 0.05 and 0.2 degrees. Taking into account that there are several potential sources of error in the control of the K value, including the mechanical control of the gap height, the accuracy of the temperature measurement system is envisioned to be 0.03 degrees or better.

The principle function of the precise temperature measurement system is to accurately measure the temperature of the permanent magnet material in the undulator. Each undulator segment will have one sensor probe. The probe cannot be directly attached to the permanent magnetic material of the undulator. It is therefore important that the probe, positioned at some distant position, measures a temperature that is representative for the undulator and its magnetic properties.

The spatial and temporal progression of the temperature in the undulator is governed by heat transfer between the surrounding air and the undulator construction and heat conduction within the undulator. In the following discussion the undulator is a homogeneous steel slab geometry with dimensions $5000 \times 680 \times 100\ mm$.

Heat Transfer and Heat Conduction

Assume a uniform increase in ambient temperature (no gradients) at the undulator. The transfer of heat between the surrounding air and the undulator construction is given by

$$\Delta Q = hA\Delta T\Delta t \tag{1}$$

where ΔQ is the amount of heat passing from the air to the undulator, h is the heat transfer coefficient, A the surface area, ΔT the difference in temperature and Δt the time. Heat will continue to flow until the air and the undulator have the same temperature. The total amount of heat that will flow to the undulator is equal to the amount of heat it takes to increase the temperature of undulator by ΔT, or

$$\Delta Q = cm\Delta T \tag{2}$$

where c is the specific heat capacity and m the mass of the undulator. Equations (1) and (2) give the characteristic time for heat transfer,

$$\Delta t_{eq} = \frac{cm}{hA} \tag{3}$$

With $c = 460\ J/kgK$, $\rho = 7.8\ 10^3\ kg/m^3$, $h = 10\ W/m^2K$ and surface area according to geometry, the characteristic time for heat transfer is,

$$\Delta t_{eq} = 1.6 \cdot 10^4\ s \tag{4}$$

According to equation (3), the characteristic time for heat transfer is independent of the difference in temperature between air and undulator. If the ambient temperature increases more, more heat will flow per unit time from the air to the undulator but at the same time it will require more energy to heat the undulator to the temperature of the surrounding air.

The flow of heat from the air to the undulator is redistributed in the undulator according to the heat equation,

$$\frac{\partial w}{\partial t} = a^2 \frac{\partial^2 w}{\partial x^2} \tag{5}$$

where $w(x,t)$ is the local temperature at any specific time and a is the thermal diffusivity, given by,

$$a^2 = \frac{k}{c\rho} \tag{6}$$

where k is the thermal conductivity, c the specific heat capacity and ρ is the density. The boundary value problem with

$$w(x,0) = f(x),\ w(0,t) = w_1\ and\ w(L,t) = w_2 \tag{7}$$

has the solution,

$$w(x,t) = \sum b_n e^{-(n^2a^2\pi^2/L^2)t} \sin\frac{n\pi x}{L} + g(x) \tag{8}$$

$$b_n = \frac{2}{L}\int_0^L (f(x) - g(x)) \sin\frac{n\pi x}{L} dx \tag{9}$$

$$g(x) = w_1 + 1/L(w_2 - w_1)x \tag{10}$$

With the undulator exposed on all sides to the surrounding air, the heat conduction will occur along the shortest length of the geometry, $i.e.$ perpendicular to the main sides. A change in temperature at the surface will propagate according to equation (8).

The characteristic time for heat conduction can be estimated from the $n = 1$ component ($i.e.$ the component with the longest time-scale),

$$e^{-(a^2\pi^2/L^2)t} = \delta \tag{11}$$

or,

$$\tau = -\frac{\ln \delta L^2}{a^2\pi^2} \tag{12}$$

The conductivity for steel is $45\ W/mK$ and with $\delta = 0.01$ (*i.e.* the temperature has reached 99% of the the steady-state value) the characteristic time for heat conduction is,

$$\tau = 3.7 \times 10^2 \ s \qquad (13)$$

Compared with the characteristic time for heat transfer (equation (4)) it is clear that heat conduction occurs on a much faster time scale than heat transfer.

In conclusion, the heat transfer between the surrounding air and the undulator construction occurs on much longer time-scale than the heat conduction within the undulator. This results in an approximately uniform temperature of the undulator and it is herefore not so critical to position the temperature sensors very close to the permanent magnetic material in the undulator to accurately measure the temperature.

Test Results from a Model Undulator

The temperature measurement system will be tested and evaluated at the mock-up undulator segment when ready in early 2011. Meanwhile, measurements on an undulator model offers the possibility to check that the temperature is indeed uniform in the undulator construction and to tests different ways to position the temperature sensor.

The undulator model is simply a homogeneous steel slab geometry with dimensions $375 \times 150 \times 80\,mm$ which gives approximately the same relation between the characteristic time for heat transfer and heat conduction as in the real undulator construction. The temperature measurement system consists of a nine channel Almemo MA8590-9 unit and several different Pt100 probes. There are several options how to connect the sensor probes to the undulator model, deep inside (representing the centre temperature), closer to the surface and directly at the surface. The undulator model with three sensors attached to it is pictured in figure 1.

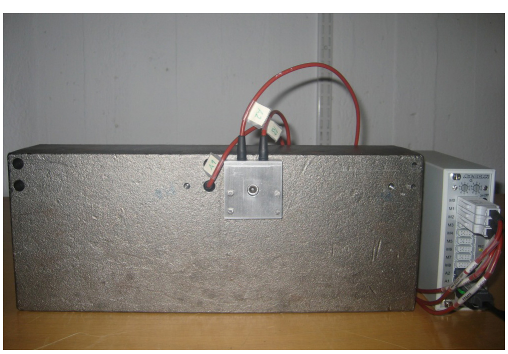

Figure 1: Undulator model with three sensors attached.

Figure 2 shows the result from a 70 hour long measurement of the temperature of the undulator model with three sensors attached. The sensors were calibrated with respect to each other prior to the measurement. Signal A1 measures the temperature in the interior, representing the centre temperature, while signal A2 and A3 measures the surface temperature. The ambient temperature changes during the day, with the lowest temperature in the morning just before the heat is switched on. The temperature sensors accurately

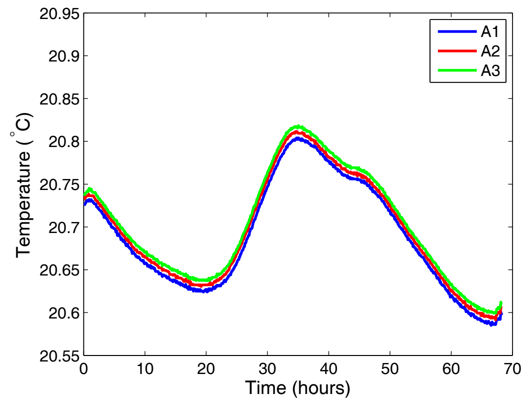

Figure 2: Undulator model temperature measured with three calibrated sensors.

measure the change in temperature but more importantly follow each other closely even though they are at different positions.

In the temperature compensation scheme, the undulator gaps are adjusted according to temperature changes. It is therefore very important that all sensor have similar response to temperature changes. Figure 3 shows the same data set as in figure 3 with three more, uncalibrated sensors added at different positions at the surface of the undulator model. Here signal A1 has been subtracted from the other signals to show the difference between the different sensors and their position. Over almost 70 hours of measurement the maximum difference in temperature is less than 0.01 degrees.

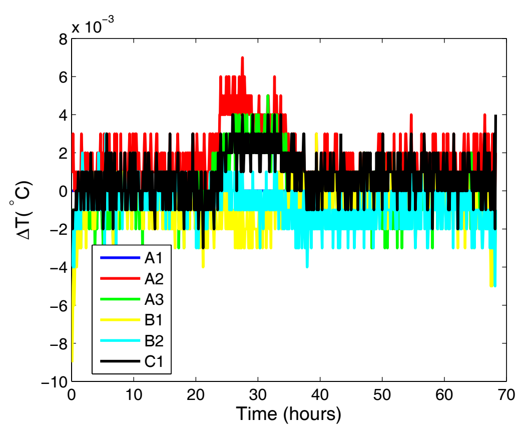

Figure 3: Temperature difference between six sensors.

The previous discussion assumed no gradients in ambient temperature around the undulator. In reality there will be gradients, along the undulator as well as in the vertical direction. The undulator gap will be adjusted to one temperature only so this temperature must be a representative one. The air-condition system of the tunnel will keep the temperature within 0.1 degrees within one undulator section (5 m), both vertically and horizontally. A temperature gradient along the undulator (the beam direction) will result in a linear temperature difference between the end points. The average value will be at the midpoint, which is the obvious position for the temperature sensor. For gradients in the vertical direction there will be a discrepancy between the temperature measured with sensor and the temperature of the permanent magnetic material. Another aspect is that the undulator construction consists of two separate blocks and there will only be one temperature sensor. However, assuming that the different parts of the undulator behave in same way and with the sensor probe positioned as close as possible, vertically, to the permanent magnetic material, the difference in temperature measured by the single sensor and the temperature of the permanent magnetic material is estimated to be negligible.

SUMMARY

In the proposed compensation scheme for the XFEL undulators, a precision temperature measurement system will provide necessary data to adjust the undulator gap to temperature changes and thereby maintaining wavelength and phase-matching conditions. Calculations show that the flow of heat between the surrounding air and the undulator construction is much slower than the redistribution of heat within the undulator. This results in a uniform temperature throughout the undulator (assuming no gradients in ambient temperature) at any time even though there is a temperature difference with the surroundings. Measurements on a model undulator with an Almemo system and several Pt100 probes meet the requirement of accuracy of 0.03 degrees and confirms that the measured temperature is independent of sensor position. It is therefore not critical to position the temperature sensors very close to the permanent magnetic material in the undulator to accurately measure the temperature.

The rotating coil setup designed for fiducialization and characterization of the XFEL quadrupole magnets has recently been upgraded with new data acquisition system, printed circuit board coils and improved mechanical support.

REFERENCES

[1] C. M. Spencer *et. al.*, SLAC-PUB-11473 (1998).

[2] F. Hellberg *et. al.*, FEL'08, Gyeongju, August 2008, TUPPH044, p. 345, `http://www.JACoW.org`

[3] A. Hedqvist *et. al.*, EPAC'08, Genoa, p. 1338, `http://www.JACoW.org`

[4] F. Hellberg *et. al.*, FEL'09, Liverpool, August 2009, WEPC15, p. 530, `http://www.JACoW.org`

[5] F. Hellberg *et. al.*, PAC'09, Vancouver, May 2009, TH5RFP088, to be published, `http://www.JACoW.org`

[6] J. T. Tanabe, Iron Dominated Electromagnets, World Scientific Publishing, Singapore (2005)

[7] Y. Yuhui, B. Faatz and J. Pflüger, Phys. Rev. ST Accel. Beams 11, 100701 (2008)