REDUCTION OF DYNAMIC FIELD ERRORS IN SUPERCONDUCTIVE UNDULATORS

S. Ehlers*, A. Bernhard, F. Burkart, A. Keilmann, P. Peiffer,
R. Rossmanith, T. Baumbach, Karlsruhe Institute of Technology, Germany
D. Schoerling, CERN, Switzerland

Abstract

The magnetic field in superconductive undulators is changed by varying the current in the superconductive wires. During operation at stable current, the electric current is confined to the resistance-free filaments. During ramping, however, the superconducting wire bundles have an inductive impedance, causing part of the current to penetrate into the iron body if electric insulation leaks between the wire and the iron body are present. If this is the case the leak currents and other eddy currents decay slowly after the ramp. The magnetic field of the undulator changes during this period. It was shown experimentally that an effective electric insulation between the wires and the iron body can minimize the current and the magnetic field drifts. In this paper the results of these experiments and simulations of the described effects are presented.

INTRODUCTION

Field transients induced in a superconductive undulator during ramping were investigated through systematic orbit position measurements at ANKA [1]. A strong ramp rate dependence indicated presence of decaying eddy and leak currents in the yoke and possibly in the wire. Also, a dependence on cycling history suggested that hysteretic effects occur within the superconducting coils. Longer-term (around 30 min) effects were attributed to flux creep within the wires. However, the different possible sources could not easily be separated through the measurements and the severity of each was unclear.

Recent simulations have increased our understanding of eddy and leak currents in the undulator. Including model errors and treating the superconducting coils as a network of current loops with possible shorts between one another gives a clearer picture of the formation and time-dependence of current distributions within the undulator.
Furthermore, measurements on two new short models have suggested that the dominant contribution to field drifts can easily be avoided through careful construction of the undulator.

MEASUREMENTS

Measurements on two short model magnets have suggested that the dominant source of the field drifts observed in earlier measurements is leak currents in the body. Firstly,

* sandra.ehlers@kit.edu

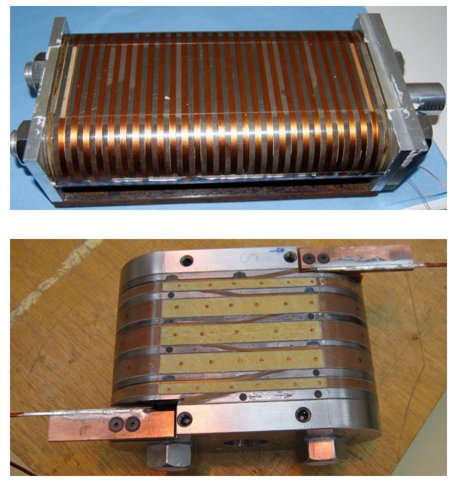

Figure 1: The two short-models on which measurements have been conducted. Top: Undulator model, 15 mm period length [2]. Bottom: Wiggler model, 40 mm period length [3].

Table 1: Parameters of the two short models

	CERN-SCW	KIT-SCU
geometry:	vert. racetrack	
straight [mm]	100	60
radius [mm]	50	30
period length [mm]	40	15
# full periods	1	13
wire:	NbTi multifilament, rect.	
dim's (insulated) [mm^2]	1.25×0.73	0.77×0.51
Cu:Sc-ratio	1.71	1.32 (?)
twist pitch [mm]	18	25
RRR Cu-matrix	> 100	> 65
experimental conditions		
operation current [A]	730	500
ramp rate [A/min]	84	150
max. field @ conductor [T]	3.3	2.3
field grad. along wire [T/m]	1.3	3.0

measurements were conducted on a short-model wiggler, fabricated and tested at CERN [3]. For the second experiment, an undulator half was used, constructed and tested at KIT [2]. Tab. 1 summarizes basic parameters of the two short models.

The geometric and electromagnetic parameters crucial for dynamic effects in the *superconducting wires* are the twist pitch and the effective coupling resistance for coupling eddy currents, and the field gradient along the wire for boundary induced coupling eddy currents [4, 5]. These parameters are in the same order of magnitude for both magnets. It is therefore admissible to assume that for a given current ramp in both magnets the contribution the superconducting wires to the field drifts is of similar order both in amplitude and time constants.

The only remaining qualitative difference between the two short models is that an additional insulating layer between coil and iron was applied in the wiggler model; the resistance is measured to 127 MΩ (150 V, 60 s). This is not the case with the undulator half. In superconductive accelerator magnets insulation is a vital measure for quench protection due to the high amounts of energy stored. On the contrary, the stored energy in superconductive undulators is low, while it is desired to pack coils and magnetic poles as dense as possible in order to achieve high on-axis fields. Thus an additional insulating layer between coil and iron has not been motivated for superconductive undulators although in this case short circuits to the winding body easily can occur.

Fig. 2 shows the field on axis measured after a ramp to 730 A for the wiggler and 500 A for the undulator, with ramp rates 84 and 150 A/min, respectively. Within 30 minutes after ramping, the field of the undulator half showed a transient behaviour similar to that observed in [1]. The wiggler — within the stability-limits of the Hall probe current source — did not exhibit any field transients. This different behaviour can clearly be attributed to the suppression of leak currents through the ground insulation.

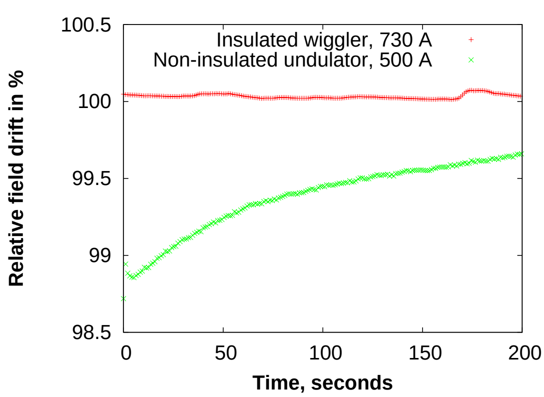

Figure 2: Field drifts after ramp from a wiggler short model and from a short undulator half, relative to the measured value 430 s after ramping.

For a simple estimation of the drifts caused by leak currents consider the circuit depicted in Fig. 4. The current source I_0 represents the power supply, the inductances L_1, L_2, L_3 represent portions of the series connection of superconductive coil packs, R_b represents the resistance of the winding body and R_c the contact resistance between the coil packs and the winding body. For the KIT-SCU short model the resistance of the winding body at 4 K is in the order of $R_b/l \approx 2 \times 10^{-10}\,\Omega/\mathrm{mm}$.

Temporal drift phenomena caused by leak currents exhibit time constants determined by the Inductance and Resistance involved in the short circuit loop,

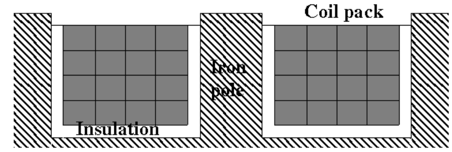

Figure 3: Insulation is needed in the grooves between coil packs and iron body.

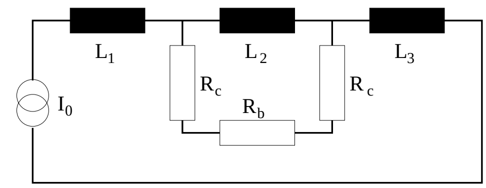

Figure 4: Scheme of a leak current circuit

$$\tau = \frac{L_2}{2R_c + R_b}. \quad (1)$$

The drift shown in Fig. 2 can be fitted with a sum of two exponentials with time constants $\tau_1 = 460 \pm 20\,\mathrm{s}$ and $\tau_2 = 32 \pm 1\,\mathrm{s}$, respectively. The inductances involved can be estimated from the energy stored in the magnetic field according to

$$L_2 = 2\frac{\int_V \mathbf{H}\cdot\mathbf{B}\,dV}{I_0^2}. \quad (2)$$

The field energy was calculated with the FEM software OPERA3D for one single period and for the complete. This calculation yielded $L_{21} = 4.7\,\mathrm{mH}$ for the complete short model coil and $L_{22} = 0.33\,\mathrm{mH}$ for a single period in the inner part of the coil. Thus the two time constants observed are consistent with the two extreme cases of a short bypassing the complete series of coil packs and a short bypassing a single period, assuming a contact resistance of $\sim 5\,\mu\Omega$.

EDDY CURRENT SIMULATIONS

Apart from the leak currents, the presumably next largest transient effect within the undulator on a timescale of seconds to minutes after a ramp is eddy currents in the iron yokes. 2D-simulations have been undertaken using the FEM software OPERA, that investigate the effect of mechanical tolerances of the undulator coils on the formation of eddy currents.

In a perfect undulator, the magnetic fields generated by the alternating powered coils within the volume of the iron body essentially cancel each other, with the exception of the matching periods at the extremities of the undulator. This cancellation, however, is disturbed by mechanical errors, in particular by coil displacements. These errors therefore result in the generation of additional magnetic flux in the iron body and subsequently in the formation of additional eddy currents. This effect is shown in Fig. 5

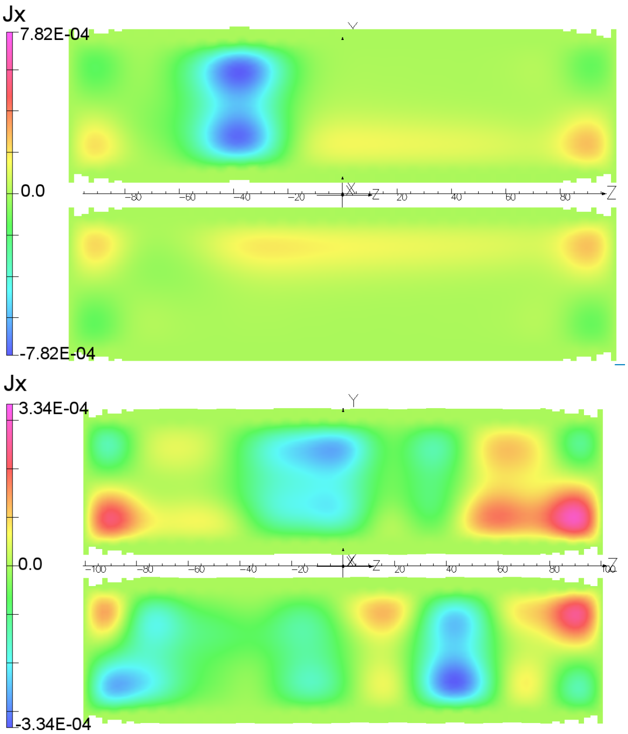

Figure 5: Eddy currents in iron yokes 100 seconds after current ramp, in model with a single pole displacement of 1 mm (top) and with randomly distributed pole displacements with $\sigma = 0.1\,\mathrm{mm}$ (bottom).

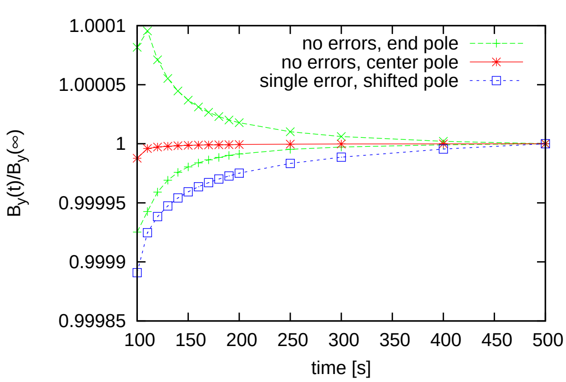

Figure 6: Time variation of the local field amplitude due to eddy currents after ramping up.

(top) for the (exaggerated) displacement of a single coil and pole by 1 mm.

A more realistic configuration with randomly distributed errors in the order of 0.1 mm resulting in a more complex eddy current distribution is shown in Fig. 5 (bottom). The eddy currents in the iron body reach similar values in the center as at the extremities. The average ohmic losses in the iron body for a current ramp to 500 A with 300 A/min are < 0.02 W per period.

For a conservative estimation of the on-axis field drift caused by eddy currents in Fig. 6 the on-axis field drift at the position of the single 1 mm-displaced pole is shown in relative units. The respective on-axis field drifts at a central and the end poles of an error-free model are shown for comparison.

The relative amplitude of the field drift is in the order of 100 ppm which is two orders of magnitude lower than the drift due to leak currents. Due to the extremely low resistivity of metals at 4.2 K, however, the time constants of these drifts, depending on the winding body geometry, can easily reach tens to hundreds of seconds.

CONCLUSION

Measurements have revealed the importance of leak currents between the coils through the iron yoke, disturbing the magnetic field in the percent range. The obvious solution is to insulate the coils from the iron, as proven by the successful drift suppression in a wiggler short model.

Other possible contributions to the field drift were smaller than the resolution of the magnetic measurement setup ($\sim 10^{-3}$).

Transient simulations have shown that non-zero mechanical tolerances lead to the formation of additional eddy currents in the winding body contributing to field drift up to a few hundred seconds after the ramp. This contribution, however, turned out to be in the order of 100 ppm even in case of strongly over-estimated mechanical errors. This contribution therefore can be regarded as negligible.

ACKNOWLEDGEMENTS

The authors want to thank R. Maccaferri, M. Karppinen, J. Mazet, and S. Clement, CERN for many valuable discussions and technical support. Thanks also to the team of the CERN test facility for conducting the measurements of the CERN Wiggler.

REFERENCES

[1] Sandra Ehlers. Temporal drifts of the magnetic fields in superconductive undulators. Master's thesis, Royal Institute of Technology, Stockholm, Sweden, 2009.

[2] Florian Burkart. Konzeption eines Messaufbaus zur Magnetfeldvermessung eines supraleitenden Undulators. Bachelor Thesis, Universität Frankfurt, 2010.

[3] D. Schoerling, M. Karppinen, R. Maccaferri, A. Bernhard, P. Peiffer, R. Rossmanith, and A. Ams. First magnetic test of a superconducting damping wiggler for the CLIC damping rings. In *This conference*, 2010. to be published.

[4] M. N. Wilson. *Superconducting Magnets*. Oxford Science Publications, 1983.

[5] K.-H. Mess, P. Schmüser, and S. Wolff. *Superconducting Accelerator Magnets*. Word Scientific, 1996.