MAGNETIC FIELD TRANSIENTS IN SUPERCONDUCTIVE UNDULATORS

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Abstract

The use of superconductive wires instead of permanent magnets allows building undulators with shorter periods or higher magnetic fields. The photon wavelength can be tuned electrically without mechanically moving the magnets. Electrical tuning however causes dynamic effects which are seen as a temporal drift of the beam orbit, requiring in principle a fast orbit correction scheme. The first systematic time resolved measurements of such drifts have been performed at ANKA. The orbit displacement during several different ramping cycles, for different ramp rates and relaxation times, has been investigated. In this contribution, the measurement results are summarized and the persistent current effects in the superconductive wires, as well as eddy currents in the yoke are discussed as possible sources for the transients.

INTRODUCTION

Unlike conventional undulators, the field in superconductive undulators is changed by increasing or decreasing the current in the magnet coils. The changing current introduces field transients that affect the electron beam trajectory through the undulator. In the superconductive undulator SCU14 at ANKA such transients have been observed [1] as drifts of the electron orbit corresponding to a time dependent change of the undulator field integrals. To prohibit these transients or find efficient correction methods, a deeper understanding of the underlying causes is needed.

Some probable origins of the field transients are dynamics in the superconductors, eddy currents and magnetization dynamics in the iron yokes [2, 3]. In the following, the characteristic decay times of the measured drifts are compared to theoretical predictions of eddy currents in the superconductors. Eddy currents in the iron yokes are investigated through simulations.

The dynamics of eddy and persistent currents in superconductors depend on wire geometry [3, 4]. A multi-strand Rutherford geometry, as used in standard superconductive accelerator magnets, allows for high current but also exhibits interstrand and boundary induced coupling currents that can have significant effects on the magnet field quality. In the SCU14 wires there are no strands; the insulated wire has a rectangular crossection with 36 filaments embedded in copper. Therefore the comparability to previous results on accelerator magnet cables is limited.

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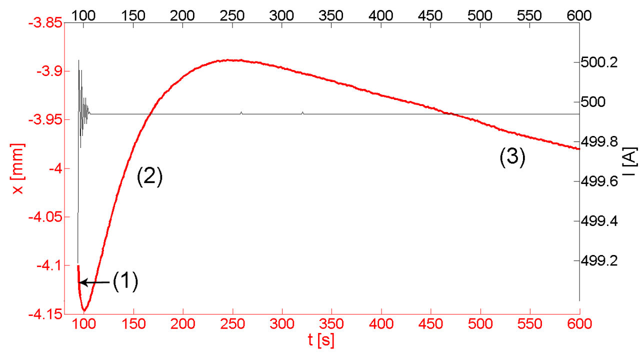

Figure 1: Drift curve during and after a 100-500 A ramp. Transient parts seen are 1. a small overshoot followed by 2. a large and steep decay, and lastly 3. a slow increase towards stabilization. The upper curve shows the corresponding current.

ORBIT POSITION MEASUREMENTS

To a first approximation the orbit displacement is proportional to a kick of the electron orbit due to an uncompensated first field integral over the undulator. This orbit position is measured with the beam position monitor most sensitive to the investigated dynamic effects. The undulator gap was set at 8 mm and the automatic orbit correction system as well as undulator feed-forward correction were turned off. The undulator was not quenched or precycled before measurements. Data of the orbit position and undulator current were taken each second during and after ramps. Several different ramping sequences between 0 and 500 A have been pursued with ramp rates of either 1, 5 or 10 A/s. The iron poles saturates at about 180 A. To follow the drift after ramping, two different relaxation times (30 and 60 min) between cycles have been used.

Results

Fig. 1 shows the orbit displacement caused by a 100 to 500 A ramp, cut immediately after the ramp and showing the three transient parts. Also shown is the undulator current, which exhibits an overshoot with an amplitude of 0.3 A, oscillation period 1 s, and damped after 25 seconds. This may contribute to, but does not alone explain the field integral drift.

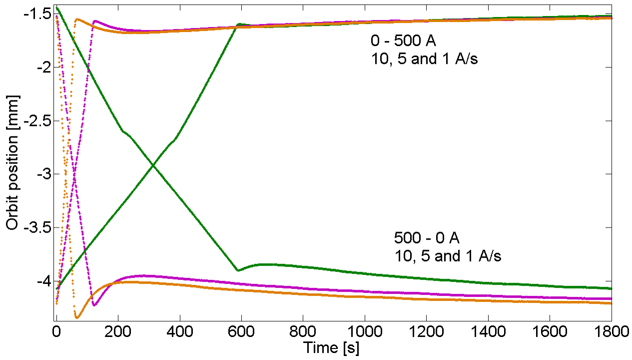

Figure 2: Ramp rate dependence for positive and negative ramps.

Immediately after the ramp (1), there is a small overshoot in the field integral. Within the next 100 seconds there is an exponential decay (2), followed by a slow increase (3) in orbit displacement, fitted with a logarithmic or double exponential function.

To compare the drift curves for different ramp rates R, final currents I_f, current steps ΔI or resting times T, the variables x_1, x_2, x_3 and x_4 are introduced, corresponding to orbit position at the start of overshoot (1), the minimum (maximum for negative ramps) value, the maximum (minimum) value and the average of the 10 last data points, respectively. From these, the decay amplitudes $D1 = x_1 - x_2$, $D_2 = x_3 - x_2$ and $D_3 = x_3 - x_4$ are deduced.

The values of x_2, x_3 and x_4 are determined by the proportionality to final current. Also the decay amplitudes D_2 and D_3 rise significantly with I_f, although in this case the current step dependence is even more pronounced.

Interestingly, the decay amplitudes are always larger for positive ramps than for negative with the same current step. This is for example seen in Fig. 2, where curves following the three different ramp rates are shown. The amplitudes D_1 and D_2 rise linearly with ramp rate, whereas D_3 is decreased. A high ramp rate clearly affect also the amount of field integral induced. Generally, for a smaller initial field integral change (corresponding to small absolute values of x_1, x_2), the slow decay D_3 is larger.

It should be noted that for the slow decay (3) to stabilize after a $\Delta I = 100\text{A}$ ramp, less than 30 min is sufficient, whereas about two hours are needed after a $\Delta I = 500\text{A}$ ramp. A slight influence of the relaxation times previous to ramps is seen.

Additionally, there is a small long-term history dependence: the more cycles previous to a ramp, the larger is the total change in field integral, an effect that is most strongly pronounced between the first two cycles. Fig. 3 show results from positive and negative ramps to the same I_f, but with larger ΔI for the negative ramps. The small history dependence can be seen; the first up-ramp curve is significantly higher than the two following, and also the first down-ramp curve is higher than the second (which was performed after a longer relaxation time). All curves approach each other due to the logarithmic decay.

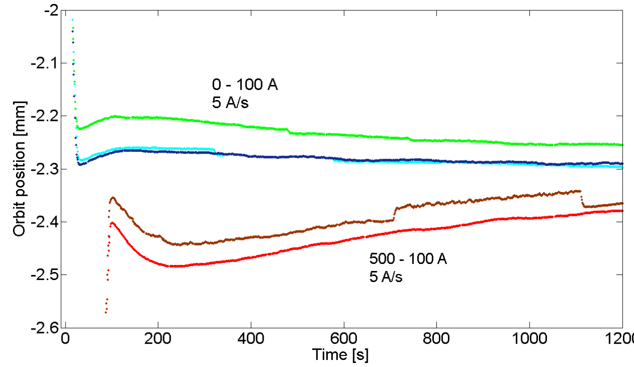

Figure 3: Drift at 100 A after up-ramp (0-100 A, upper curves) and down-ramp (500-100A, lower curves).

SOURCES OF TRANSIENT EFFECTS

The measured drift originates from dynamics in the superconductors and in the iron yokes, appearing when changing the undulator current.

Persistent currents in the filaments are particularly important in the low field range where an undulator is operated. They are history dependent since currents screening new changes in the field will superimpose on the ones already present. Furthermore the flux change from screening currents from a decreasing field is smaller than from a field increase [8], a hysteretic behaviour compatible with our measurements. Persistent currents are always present, and reduced only by using finer filaments.

There can be different kinds of coupling effects in a superconductor. *Filament coupling* currents follow the resistance-free filaments but occasionally jump through the copper matrix to nearby filaments. In wires with a small filament twist pitch they have a decay time beneath a second [3]. As mentioned before, inter-strand coupling is not relevant in the SCU14 wire. However, some kind of *boundary induced coupling*, due to a changing field gradient along the wire [4], may occur and have longer time constants than other superconductor eddy currents. Their influence is largely unknown in the present wire design. Normal eddy currents also flow in the copper matrix, their decay time is, however, very short [3].

Coupling currents in general depend strongly on ramp rate, as opposed to the persistent currents. Thus the measured R dependence indicate presence of coupling currents.

A further effect in a magnetized superconductive wire is *flux creep*, causing a slow magnetization decay [9, 10] which is consistent with the logarithmic decay of the drift.

Eddy currents are also induced in the yoke iron. First results of the simulations of eddy currents in the iron yokes are presented in the next section.

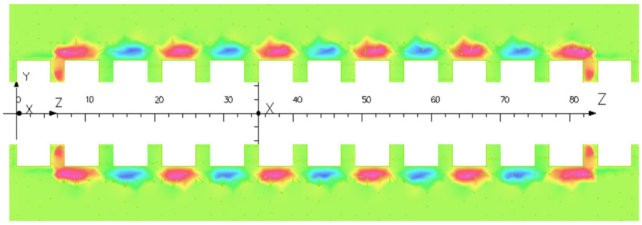

Figure 4: Close-up on eddy currents formed in iron yokes during current ramp. Red areas indicate current in positive x-direction (inwards), blue areas in negative x-direction. Note the large end pole eddy currents.

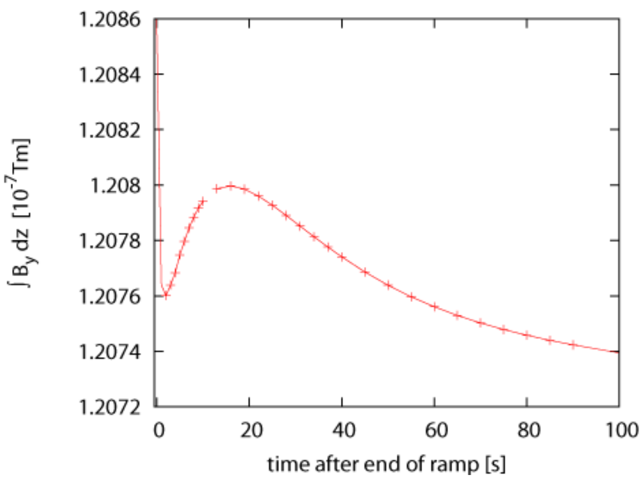

Figure 5: Time variation of the 1st field integral after an up-ramp, caused by eddy currents in the iron yokes.

SIMULATIONS

A model of the SCU14 with 3 full periods plus end periods was built in Opera, allowing to follow the dynamics of the magnetic field distribution in the iron yoke and wire bundles during and after an up-ramp. Keeping in mind that calculations are done for a perfect undulator field, and that conductivities in the materials are not precisely known, preliminary results show some interesting features. The distribution of eddy currents in the iron, Fig. 4, suggests that the end poles may have a larger effect on the field integrals than the center poles.

Fig. 5 displays the complex temporal behaviour of the first field integral immediately after a ramp. It behaves similar to the orbit position curves except for the shorter time scales involved. The process is still surprisingly slow regarding the significantly higher resistance in the iron, and may be even larger in a full-period model. It should be noted, though, that the magnitude of induced field is quite small in present calculations.

Persistent and eddy current effects in the conductors will be included in the model, especially boundary induced coupling currents need further investigation. Preliminary results on eddy currents in the copper matrix disclose very short decay times, in agreement to theory [2].

CONCLUSION

Measurement results disclose that several effects may be involved in the field dynamics, with decay time constants from below a second up to an hour. Persistent currents in the wires are probably a main source of the field integral drift, explaining the hysteretic differences from negative ramps as compared to positive, as well as the history dependence. Ramp rate dependence could be explained by decaying coupling eddy currents. Due to the wire geometry, only filament coupling or some kind of boundary induced eddy currents could be present. In the late part of the drift after a ramp, flux creep is a probable source of the slow decay. Simulations disclose that iron eddy currents cannot be excluded as additional source of the drift. More investigations on these and on superconductor current effects are planned.

Interestingly, many results, like the history and ramp rate dependence of the transient field, as well as time constants of the transients, are suprisingly consistent with results on time drifts in accelerator dipole magnets [5, 6, 7], spite of the great differences in design.

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