FIELD ERROR COMPENSATION AND THERMAL BEAM LOAD IN A SUPERCONDUCTIVE UNDULATOR

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Abstract

During the last few years prototypes of superconductive undulators have been built and tested [1,2]. Measurements of the magnetic field showed that both the first and the second field integral are, as expected, not fully compensated and that a small but not negligible phase error exists. In order to compensate for these errors, electric shimming techniques are applied. Integral shimming is already part of the two 14 mm undulators under construction. The electric phase- shimming is still under investigation. At the end of this paper the thermal beam load for a small-gap superconductive undulator is estimated defining the layout of the cooling system.

STATUS OF THE SUPERCONDUCTIVE UNDULATOR PRODUCTION

After early attempts [3,4] to build a superconductive undulator in Stanford and Brookhaven, ANKA and ACCEL together developed a new concept described in [5]. Four superconductive undulators based on these new concept have been built or are in the process of being built: a 3.8 mm period length, 100 period long undulator has been tested with beam, a 14 mm ten period long undulator prototype has been built and the magnet field was measured. The construction of a 14 mm period length, 50 period undulator to be installed at the University of Singapore/ Singapore Synchrotron Light Source has just been completed and is now waiting to be tested. A 14 mm/ 100 period long undulator equipped with a cryostat suitable for operation in a storage ring with a minimum gap of 5 mm is under construction.

The field data of the 10 period undulator were analysed in detail [2] and the following arguments are based on these findings.

CORRECTION OF THE FIRST AND SECOND FIELD INTEGRAL WITH SUPERCONDUCTING CORRECTION COILS

The 10 period superconductive undulator as seen from the beam is shown in fig. 1. The field measurements are discussed in detail in [2].

The calculated beam trajectory from these data is shown in fig. 2. In order to compensate the trajectory, superconductive coils parallel to the beam are installed as shown in fig. 3 (green wires).

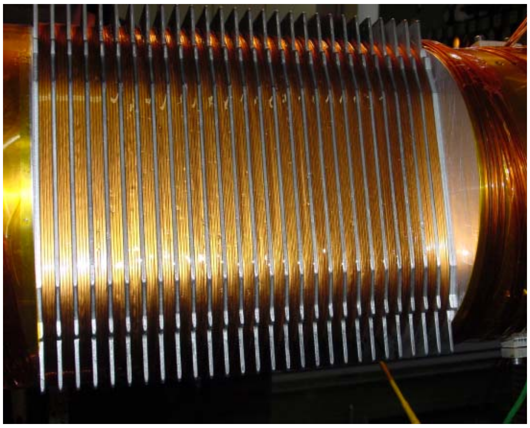

Fig.1: the 14 mm test undulator (one half of the undulator) .Shown is the side close to the beam.

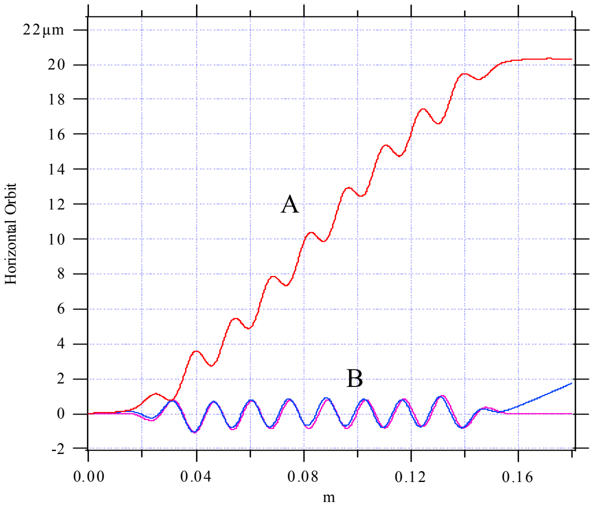

Fig. 2 Calculated trajectory (A) without the correction coils shown in fig. 3, (B) corrected trajectory with the superconductive coils shown in fig. 3.

ELECTRIC PHASE SHIMMING

As in the case of a permanent magnet undulator, there may be need for phase shimming. The measured phase error of the undulator (fig. 1) is shown in fig. 4.

The proposed shimming is done with superconductive wires. The arrangement of the phase shimming wires is shown schematically in fig. 5. The shimming wires are thin wires parallel to the existing wires. The wires can be powered separately.

The changes in the field are shown in the lower part of fig. 5. Using this wire arrangement, the field is only affected in one half period. The form of the field change is similar to the form of field change at phase shimming with permanent magnet undulators.

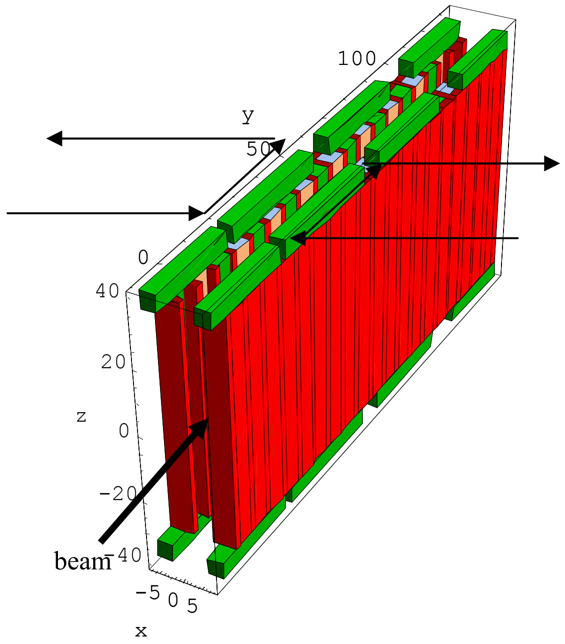

Fig. 3 Model of the superconductive undulator with the iron and the superconductive wires. The additional correction coils are parallel to the beam.

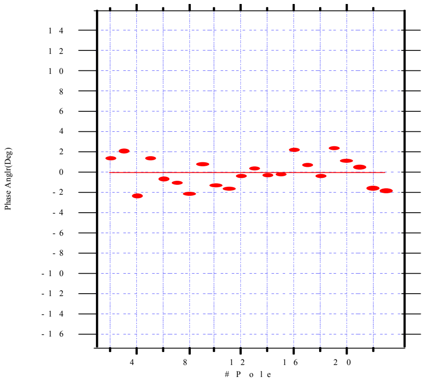

Fig. 4 Measured phase error of the undulator prototype shown in fig. 1

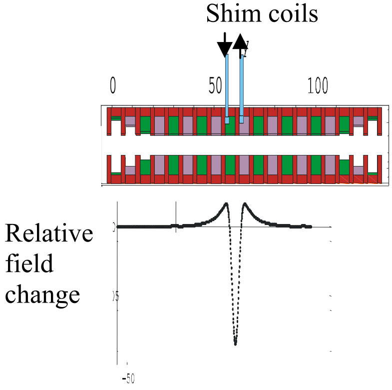

Fig. 5 Principal idea of local phase shimming

RESISTIVE WALL HEATING BY THE BEAM

The indirectly cooled superconductive undulator is heated by the beam (resistive wall effects). In the following the magnitude of this effect is estimated.

The parasitic heating of a surface by unit length P/L caused by the beam is [6]:

$$P/L = \frac{I_{av}^2}{M.f_0.L}\frac{c^2}{\pi}\int_0^\infty S^2(\omega)R_{wall}(\omega)d\omega \tag{1}$$

where I_{av} is the average current, M are the number of bunches, f_0 is the revolution frequency, L is the circumference of the accelerator, R_{wall} is the wall resistance and S is the bunch spectrum:

$$S = \frac{1}{c}\exp\left[-\frac{\sigma_z^2\omega^2}{2c^2}\right] \tag{2}$$

Integrating equation (1) and using the relation

$$R_{wall} = \frac{L}{2\pi r}\sqrt{\frac{\omega\mu_0\rho}{2}} \tag{3}$$

where $\mu_0 = 4\pi 10^{-7}$ Vs/Am, r is the shortest distance between beam and surface and ρ is the resistivity of the surface material in Ohm.m. Combining these formulas yields

$$P/L = 1.225\frac{1}{4\pi^2 r}\left(\frac{c}{\sigma_z}\right)^{1.5}\sqrt{\frac{\mu_0\rho}{2}}\frac{I_{av}^2}{M.f_0} \tag{4}$$

In equation (4) for a given geometry the only unknown parameter is ρ. At low temperatures ρ for a given material depends on various parameters:

a.) The temperature. In the following it is assumed that the surface is copper. The values of ρ depend on the quality of the material [7]. Copper used for coating has a resistivity of $1.7.10^{-8}$ Ohm.m at room temperature and a resistivity of $2.8.10^{-10}$ Ohm.m. The resistivity at low temperatures is reduced by a factor called RRR (Residual Resistance Ratio) and this factor is close to 61. This high RRR factor is one of the advantages when operating magnets with a cold bore. The heat load is reduced dramatically, but at the same time the transport of heat at low temperatures also becomes very limited.

b.) The magnetic field. The resistivity depends on the magnetic field. This dependency is described by the Kohler law [8]:

$$\rho(B,T) = \\ = \rho(B=0,T).\left(1+10^{(1.055.\log(|B|.RRR)-2.69)}\right) \quad (5)$$

c.) The anomalous resistivity effect. Equation (3) is not strictly valid for higher frequencies [9]. The deviations vary with the structure of the surface and are difficult to predict using theoretical methods. Measurements are necessary to evaluate the magnitude of this effect.

In the following the magnitude of the effects are estimated for ANKA. Starting point is a ρ of $2.8.\ 10^{-10}$ Ohm.m according to a.). This value has to be corrected for the magnetic field. according to b.). The maximum assumed undulator absolute field (ANKA-undulator: 1.5 T at a gap of 5 mm) has to be averaged over a full period. The averaged field is only about 60 % of the maximum field. This leads to a final ρ of $3.5\ 10^{-10}$ Ohm.m for a maximum field of 1.5 T.

Based on these assumptions the deposited power for the ANKA undulator according to equation (1) is about 200 mW/m for a gap of 5 mm, a beam current of 200 mA and a bunchlength of 1 cm.

It has to be noted that a reduction in bunch length limits the use of superconductive undulators. A bunch length reduction by a factor of 3 brings the heat load for an ANKA-type undulator above 1 W (assuming otherwise unchanged parameters). This would require a different cooling system and could mean that the idea of using only cryo-coolers is no longer acceptable.

The anomalous effect c.) is not well documented but, extrapolating from measurements, the heat load might increase by up to 20% depending on the type of surface treatment. As a result the copper-coated shield must be carefully prepared in order to minimise the unwanted heat load.

Summarizing this chapter, the superconductive undulator is almost ideal for low gap operation as long as the bunch lengths are not excessively short at average currents of about 200 mA. The high electrical conductivity at low temperatures prevents the build-up of excessive heat load. Also excessive pumping for the small gaps is not necessary since the gap temperature is close to 4 K.

THE PROPOSED MEASUREMENT OF THE HEAT-LOAD AT ANKA

In order to obtain experimental data on the heat load, it is intended to conduct a beam test at ANKA . The test equipment is shown schematically in fig. 6.

The superconductive undulator (red blocks in the center of the drawing) will be installed in one of the four straight sections of ANKA. The period length is 14 mm, the undulator is 100 periods long. The undulator will be equipped with corrections for compensating the first and the second integral (see fig. 3) but not with phase shimming coils.

The vessel surrounded by the undulator is cooled to 4 K by cryo-coolers schematically shown in the center of the cryostat. The outer vessel is cooled to 60 K.

The gap of the undulator can be varied in steps. At injection at 500 MeV and during ramping, the undulator gap is fully opened to 25 mm. In this position the undulator cannot be powered. The gaps at which it can be powered are 5mm, 8 mm, 12 mm and 16 mm.

In order to protect the undulator, a scraper in front of the undulator is opened and closed to the same gap width as the undulator. A horizontal scraper pair, not shown in this diagram, protects the undulator from synchrotron radiation.

The flanges of the undulator are equipped with valves making it possible to remove the undulator from the beamline and replace it by a normal beampipe even when the undulator coils are still cold. The measurement of the temperature of the cryocooler system makes it possible to measure the beam-induced heat.

The beam pipe vacuum is separated from the insulation vacuum. This parts in the storage ring vacuum have only metalic surfaces.

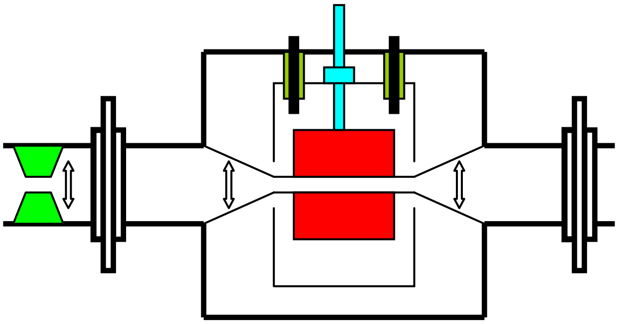

Fig. 6 The planned test at ANKA

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