A new method for measuring the magnetic field in a microwiggler based on magnetic tape recording

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The new generation of FELs should be more compact than present designs. One important way to achieve this size reduction is to use microwiggler. Measurement and mapping of the magnetic field inside electromagnetic microwiggler is at present a difficult task because of the small dimensions of the microwiggler, the requirement for high spatial resolution in the measurement of the magnetic field, and the need to obtain a fast response since the field-producing pulse may be of short duration.

We present a new method for quick measurement and mapping of the microwiggler field. Like the pulsed wire method [1,2], it gives in one measurement the magnetic field variation along the entire length of the electromagnetic wiggler. In addition it is possible to also measure, instantaneously, the distribution of the magnetic field across the lateral dimension of the wiggler.

Our method is based on the use of a magnetic recording tape which is inserted into the gap of the electromagnetic microwiggler. The maximum local magnetic field produced during the driving-current pulse is recorded on the tape at all axial and lateral positions. The tape containing the recorded magnetic field can then be read (and “heard”) by an ordinary tape recorder.

1. Introduction

It was recently pointed out [1] that the development of electromagnetic microwiggler is the best way to make FEL systems more compact and make them operate at short wavelengths. Permanent magnet microwiggler cannot give the desired strong field because the size of the magnet and the field strength are related. For this reason electromagnetic wiggler are being developed which can create magnetic fields of the order of 5 T and more [1] and which have the desired short periods. The new electromagnetic microwiggler carry high peak currents (typically kA). They typically have periods of 2–4 mm and have slit gaps of 1–2 mm.

The magnetic field in each period must be very nearly the same [2] so that electrons will not stray and strike the wiggler. This problem is very important in microwiggler because of their small dimensions; one must, therefore, measure the magnetic field and correct it so as to reduce field variations from period to period.

Existing means for measuring magnetic fields are Hall-effect probes or the pulsed wire technique. The Hall-effect probe is normally of the order of 1 mm in diameter and is, therefore, not suitable for field distribution measurements across 1 mm gaps. Also its resolution in the axial direction is of the order of 1 mm. The temporal response of the Hall-effect probe is of the order of 1 ms. Therefore pulses of 0.1 ms applied to microwiggler can be read only with the help of integrating circuits and the readings are, therefore, not accurate. The pulsed wire method can be used for measuring microwiggler magnetic fields having a period of 3–4 mm but for shorter periods the displacement of the wire is insufficient to provide satisfactory measurements.

In our experiments we found that the pulsed wire method was not sensitive enough to measure the microwiggler which are under development at Tel-Aviv University. There are ways to improve the pulsed wire system, but we believe that it will not be useful for small microwiggler.

The magnetic field measurement described in this paper enables measurements on wiggler having a period of less than 0.1 mm. This method, therefore, opens new possibilities for measuring wiggler having an order of magnitude smaller period than that possible with previous methods.

In this paper we shall describe this new method and experiments made on a wiggler of 31 periods (each period is 4 mm long). The maximum magnetic field created in this wiggler by a pulse of 1.1 kA was 1400 G (along the z axis). We use a standard tape to record the transverse field \( B_y \). The tape is designed to normally record an axial field, \( B_z \), but at the plane \( y = 0 \) (the wiggler midgap), where \( B_y = 0 \), it still records \( B_y \). More accurate \( B_y \) recordings would be obtained using
a tape designed to record a perpendicular magnetic field; one could thus obtain an accuracy of better than 5%.

2. Experimental method

2.1. Microwiggler to be measured

We developed an electromagnetic microwiggler permitting high current pulse flow, thus creating a strong magnetic field $B_y$ perpendicular to the axis $(z)$ and varying periodically as a function of $z$. The microwiggler consists of two slotted strips of copper, each 1 mm thick. The microwiggler has a period of 4 mm; there are 31 periods. The two strips are inserted into an aluminum fixture and are fastened to one another by screws; two Teflon strips separate them creating an air gap of 2 mm.

The magnetic field inside the microwiggler is produced by discharging a capacitor through a SCR and the two microwiggler strips. A pulse of 1.1 kA and 100 $\mu$s duration was thus produced. The maximum magnetic field, perpendicular to the $z$ axis, was 1400 G.

2.2. Magnetic field recording and reproduction on tape

An external field, $H$, applied to a ferromagnetic crystal material causes the domains to be aligned in the direction of the magnetic field. The removal of the magnetic field causes the domains to reorganize themselves to their former disorder if the applied field was weak. In the case of a strong magnetic field the process is irreversible and the domain’s internal magnetization changes as a function of $H$ along a hysteresis curve (fig. 1). Initially by increasing the external field, $H$, points $P_1$ and $P_2$ on the hysteresis curve are obtained. If the external field, $H$, is removed the magnetic material retains a permanent residual magnetic field, $M_i$, and $M_r$, respectively [3].

In order to reduce the magnetization of the material to zero the applied external magnetic field must be reduced to a negative value. This field is called the coercive field $H_c$. In this work we used a magnetic tape of a commonly used tape recorder. The tape was inserted into an electromagnetic wiggler and was magnetized during a pulsed-current flow. The magnetization process is nonlinear as can be seen from fig. 1, but there is a one to one monotonical relation between the recorded magnetization and the wiggler field since $M_1$, $M_2$, $\cdots$ are monotonical functions of $P_1$, $P_2$, $\cdots$.

2.2.1. Recording

Recording media must possess reasonably high $H_c$ and rectangular hysteresis loop shapes. These properties are obtained by means of magnetic anisotropy in the magnetic film. Such anisotropy means that less energy is required to align the magnetization in certain

![Fig. 1. The magnetization $M$ vs the applied field $H$.](image-url)
preferred directions: "easy direction of magnetization" [4]. Other directions, "hard direction of magnetization", require greater amounts of energy.

In general an externally applied magnetic field magnetizes the tape in three dimensions. If the tape is magnetized in the same direction as the tape's movement the recorder is called a "longitudinal recorder" as shown in fig. 2 and marked by A. The recording is called "transverse recording" if the magnetization is across the tape (B in fig. 2). If the recording is perpendicular to the direction of the tape's movement it is called "perpendicular recording" (C in fig. 2).

In the case of the electromagnetic wiggler we are interested in measuring the $B_y$ magnetic field component. Because of the small air gap in the wiggler the magnetic tape can only be inserted as shown in fig. 3; however, one would like to record the perpendicular magnetic field. For this reason it would be preferable to use a perpendicular-recording tape in order to measure the $B_y$ component.

In general a perpendicularly recording system has many advantages [5] over one that records longitudinally. The basic feature of perpendicular magnetic field recording is that the demagnetization field acting in the medium decreases to zero as the recorded wave-length is reduced. Therefore, for high density recording, such as is required for digital recording, a very sharp transition of magnetization is useful. By using this type of tape the field $B_y$ would, therefore, be recorded more accurately; for this reason it could
be used in principle for measuring the magnetic field in very small wiggles with a period length as short as 0.1 mm and less.

2.2.2. Reproduction

Reproduction of signals requires the tape to move at a constant velocity $v$ with respect to the reproduction head. The head converts the magnetic field to an electric current.

Most of the magnetic field flux due to the tape passes through the head due to the strong permeability of the head as compared to air. Due to the temporal variation of this field as the tape moves an electrical voltage is generated in the coil which is wrapped around the iron core of the head. The relation between the magnetic field and output voltage is:

$$ e = -N \frac{d\Phi}{dt} = -Nd\frac{\Phi}{dz}, $$

where $N$ is the number of turns in the head, $\Phi$ is the magnetic flux, and $v$ is the tape speed in the $z$ direction.

For a sinusoidal signal with a wave number $k = 2\pi/\lambda$ the created magnetic flux is:

$$ \Phi = \Phi_0 \left( \cos \frac{2\pi}{\lambda} z \right), $$

where $\Phi_0$ is the maximum amplitude of the flux which permeates the head. Substituting eq. (2) into eq. (1) the maximum output voltage $E$ is:

$$ E = -\frac{2\pi N \Phi_0}{\lambda} = -2\pi N \Phi_0 f, $$

where $f$ is the reproduction frequency and is given by $f = v/\lambda$. From eq. (3) we note that the output voltage is proportional to the recorded field.

3. Measurement of magnetic field components

3.1. The measurement system

The magnetic tape passes through the microwiggler and it is held by clamps. The microwiggler is placed on micrometer screws enabling it to have six degrees of freedom: the magnetic tape can thus be successfully placed in the plane $y = 0$.

The reproduction system consists of a Philips tape reel recorder (Model # 4308). The tape can move at two velocities (in relation to the reproduction head: 9.5 in./s or 4.75 in./s. We used the higher speed only in order to obtain a strong signal. Only the mechanical system of the tape recorder was used; we built a polar head which was inserted into the tape recorder.

3.2. Measurement of the magnetic field $B_y$

In the previous section we described the need to record the magnetic field in the direction perpendicular to the tape motion. Unfortunately we have only a longitudinally recording tape available. This means that this tape "prefers" to record $B_x$.

If the perpendicular and longitudinal fields are of the same magnitude a tape having longitudinal magnetization will record mainly the longitudinal field. However, if the longitudinal field is weak (its magnitude is

![Fig. 4. The calculated and measured magnetic fields. --- $B_z$ calculated from eq. (5), --- $B_y$ calculated from eq. (4), --- $B$ measured.](image-url)
lower than the value $P_0$ on the hysteresis curve in fig. 1) but the perpendicular field is very strong (with a magnitude much higher than $P_0$) then only the perpendicular field will be recorded on the tape.

We assume that in our case the wiggler magnetic field nearly satisfies the ideal field expressions given by eqs. (4) and (5):

$$B_y(y, z) = B_0 \cosh(k_w y) \cos(k_w z),$$  \hspace{1cm} \text{(4)}

$$B_z(y, z) = -B_0 \sinh(k_w y) \sin(k_w z).$$  \hspace{1cm} \text{(5)}

A magnetic tape placed at the plane $y = 0$ (fig. 3) will be exposed to the perpendicular field only ($B_s(0, z) = 0$ in eq. (5)); $B_y$ is, therefore, the only component that will be recorded. This is the field component we need to measure.

In practice it is difficult to place the magnetic tape exactly at $y = 0$. But from eq. (5) we see that $B_z$ has the form $\sinh(k_w y)$, so that there is always a region near the plane $y = 0$ where the magnetic field is weak enough so that $B_z < B_s(P_0)$. We assume that in this region $B_z$ shall not be recorded and the tape will
measure the strong transverse field. To confirm this assumption we performed two experiments:

1) The tape was placed inside the microwiggler diagonally (at an angle to the x axis) and the magnetic field was recorded. In fig. 4 we note that the recorded magnetic field in the central region from A to B has a periodic behaviour which is different from that near the beginning and the end of the wiggler. Over most of the wiggler length (outside of the region between A and B) the measured magnetic field has an amplitude and phase similar to the axial magnetic field as calculated along the diagonal path of the tape (note that at the center of the wiggler there is a 180° phase jump in \( B_z \) due to the sign reversal of \( \sin(k_w y) \)). In the region between A and B the phase of the measured field follows the phase of the strong \( B_y \) magnetic field, and we conclude that in this section the tape recorded the transverse magnetic field.

2) The magnetic field was recorded; once at the plane \( y = 0 \) and a second time at \( y = 0.5 \) mm. The beginning of the tape was marked in each recording by a magnetic marker. In fig. 5 we note that there is a displacement of a quarter of a period between the measured fields of \( y = 0 \) and \( y = 0.5 \) mm. Consistent with eqs. (4) and (5) we conclude that when the tape was placed at the plane \( y = 0 \) we recorded \( B_y \) only, while at \( y = 0.5 \) mm it recorded \( B_z \). In our experimental setup we found that the region in which the magnitude of \( B_z \) remains lower than the minimum recordable magnitude is between the planes \( y = \pm 0.1 \) mm. In order to measure the transverse magnetic field, which is the relevant parameter for a FEL, we made sure in all our subsequent measurements that the tape is placed exactly in this region.

4. Discussion

Fig. 6 shows an example of the magnetic field \( B_y \) that was measured using this method. In order to calibrate each measurement we estimated the value of the peak of the periodic magnetic field using a Hall probe measurement of the wiggler field at low (dc) current (5–20 A) and extrapolated to the pulsed current intensity (1.1 kA). This determined the calibration of the field measurement to a peak value of 1400 G (fig. 6).

We note that our new method is suitable for measuring microwiggles with very small period lengths. If perpendicularly recording magnetic tape were available, greater accuracy would be obtained. The maximum and minimum frequency that can be recorded is limited. The maximum frequency depends on the material of the tape, and on the demagnetization forces inside the tape. The tape of an audio cassette tape recorder, used in our experiments, permits a maximum recorded frequency of 20 kHz; this corresponds to a wiggler with a period length of 0.12 mm. The minimum frequency is limited by the reproduction head characteristics (at low frequency the electromotive potential – eq. (1) – becomes very small).

Using our recording and reproduction system we can measure wiggles with a maximum period of 10 mm. In order to measure wiggles having a greater period one has to use a higher tape velocity. For the microwiggler used in our experiments with a velocity of 9.5 in./s the minimum reproduction frequency is 60 Hz.

The maximum and minimum field strengths that can be measured using our method are also limited. The maximum field strength depends on the magnetic material used in the tape. The tape, much like a regular magnet, cannot be magnetized above its saturation level. Regular recording tape made of \( \gamma Fe_2O_3 \) can give a maximum field density of 2 T. Using a Fe tape [7] one can record field densities of up to 3.5 T. The minimum field strength which can be recorded depends upon the coercivity of the magnetic material; for \( \gamma Fe_2O_3 \) tapes the coercivity is \( H_c = 250–350 \) G; one cannot record field strengths lower than \( H_c \).

In our experiment the minimum field strength that could be recorded was 350 G; thus with \( B_z < 350 \) G near \( y = 0 \) we could record \( B_y \) only.

Noise is always added to the recorded field. Noise results from former recordings incompletely erased and from internal noises of the tape recorder itself. The method used to solve the noise problem was via averaging over 20 different measurements. Each measurement was taken independently by rolling the tape and firing a new energizing current pulse through the wiggler. A magnetic marker helped to determine accurately the relative position of the different measurements.

References