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LIMITATIONS ON THE USE OF THE PULSED-WIRE FIELD-MEASURING TECHNIQUE *

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As wigglers become longer and the wavelength of the light they produce becomes shorter, the requirements for magnetic field uniformity and precision of wiggler construction become more severe. Techniques used to measure magnetic fields and to estimate the performance of wigglers are now being pushed to their limits in precision and are generally awkward and time consuming in practice. A new field-error measurement technique has been developed that has the usual advantages of a null technique, demonstrates high sensitivity to field errors, and is rapid and simple to employ. With this technique, it appears practical to use computer control to both measure and correct field errors. In a particularly attractive application, these measuring and correcting steps could be carried out on a daily basis for an operational wiggler, which is mounted under vacuum in its optical cavity. In this way, changes in the fields caused by aging or by thermal or radiation-induced deterioration effects could be rapidly identified and corrections could be instituted without significant interruption to normal operations. The principles and limitations of this technique will be described and examples given of various implementations that have been examined experimentally.

1. Introduction

Making a wiggler for synchrotron or FEL light sources is a complex process. As normally carried out, the fabrication takes place in four steps: measuring to characterize the individual magnets, assembling the magnets, testing the fully assembled wiggler, and adjusting the wiggler to correct for "bad" magnets. The

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difficulties are centered on the large variability [1] (several percent) found in the properties of the magnets and the lengthy process involved in fully characterizing them. Ideally, the magnetic field generated by each magnet should be measured along the complete path followed by the electron beam, and the first and second integrals of the field should be evaluated because they are proportional to the bend angle and displacement of the electrons. Such measurements are normally made point-by-point using a Hall probe, and great care is taken to minimize the nonlinearities and calibration errors to provide accurate measurements [2]. Because of the time-consuming nature of these measurements and the large number of magnets in the usual wiggler, such complete measurements are rarely performed on separate magnets but are made only with the completed wiggler. As a substitute, much simpler measurements are made on individual magnets to provide some guidance as to their strengths. Among these measurements are an evaluation of the total magnetic moment, a measurement of the field strength at the position of closest approach of magnet and electron beam, and measurements made at several special places near the magnets.

The procedures used to assemble these partially characterized magnets into complete wigglers are of the utmost importance. The major technique used is to pair magnets so that a magnet that is unusual in some property will be followed by another one with a matched and partially cancelling abnormality. One can carry this matching procedure to a high degree of complexity [2], but often insufficient knowledge about the individual magnets makes this process unprofitable.

It is not too surprising, then, that large field errors are often found when a fully assembled wiggler is first tested [3]. The most common technique for fixing this problem is to identify one or more magnets that can be replaced or shifted around so as to flatten the field. This is an awkward and somewhat dangerous (because of the large forces involved) process.

Finally, when these adjustments are completed, the wiggler is penetrated with a vacuum pipe containing various focusing, steering, and diagnostic paraphernalia; is moved to its final site; and is put into use. Two new hazards are now present. First, the final site includes all the paraphernalia mentioned above and is usually crammed with pumps, electromagnets, and other kinds of magnetic hardware. The weak stray fields associated with these devices (as well as the earth's magnetism) are difficult to measure with sufficient precision, yet they contribute to major uncertainties in the field integrals that determine the deflection of the electron beam. Secondly, in use, the wiggler magnets encounter various kinds of thermal and radiation exposure that may affect their field strengths. Once the wiggler is in its final site, there is no good way to monitor the fields to detect possibie changes of this kind.

There are two related problems [4,5] encountered when using a defective wiggler: (1) the electron beam may be deflected abnormally by a magnet so that it wanders transversely, completely out of contact with the laser beam, or (2) the transverse velocity that the beam accumulates from successive deflections may be excessive so that the longitudinal velocity drops below the value needed to satisfy the resonance condition. Both problems become worse as the wiggler gets longer and as the wavelength shifts to shorter values.

To help solve these problems, a new system has been developed for assembling wigglers [6]. This system is based on a new technique for rapid and accurate measurements of field integrals. This technique has major advantages over the older techniques in at least three applications. The field integrals of individual magnets can be measured easily, providing much more complete information to be used in the matching process described earlier. The field of a completed wiggler (or a segment of it) can be measured while the magnets are being adjusted, to find an acceptable setting quickly. The measuring technique can be permanently installed in an operating wiggler; periodic measurements can be made that will show, for example, the presence of foreign fields from nearby paramagnetic sources or the occurrence of magnet degradation due to radiation or thermal effects. Not only can such deviations of the wiggler from perfection be detected, but also corrective actions can be initiated easily through the use of external steering coils, possibly completely under computer control.

The new measurement technique that makes all of this possible is based on a thin wire that is stretched near the magnet or wiggler under test, along the path followed by the electron beam. When a current pulse is passed through the wire, a force is exerted down the length of the wire that is proportional to the magnitude of the local transverse field component. The force evolves into a wave on the wire that propagates from the vicinity of the magnet to a sensor placed conveniently along the wire. The sensor we use is a commercially available component [7] that operates by both generating and detecting a light beam. The wire partially obstructs this light beam. Because of the dynamical properties of the wire and the response of the sensor, the sensor's output versus time is proportional to the integral of the field versus position along the wire. Therefore, the wire motion is an analog of the electron beam motion and the resulting information is transported to the sensor from deep within the wiggler. To make the analog between electron beam and wire even more complete, the use of a step-function current pulse rather than a delta-function pulse generates a sensor output that is proportional to the second integral of the field, in direct analogy to the electron beam displacement.

A more complete explanation of the new system and descriptions of experimental examples of the measurement technique are presented elsewhere [6]. Briefly, these measurements show that the new technique is very successful in measuring the properties of single magnets and short wigglers or segments of longer wigglers. Its use in this application should, we believe, become widespread. When measuring long wigglers, however, problems are encountered: the wire sags because of its weight, shifting it out of the region of interest; and, because of certain wire properties, the wave propagating along the wire becomes distorted, falsifying or obscuring the field measurements. We have performed measurements with long wires (greater than 15 m) to clarify the nature and magnitude of these effects, and we have conducted theoretical analyses of these problems. This paper gives our results.

2. Derivation of relationships for the wire's deflection

2.1. Delta-function excitation

Ideally, the deflection of a wire can be expressed as the sum of two waves traveling in opposite directions,

$$y(z,t) = f(z - c \cdot t) + g(z + c \cdot t),$$

where f and g can be any functions, and c is the wave velocity $\sqrt{T/P}$, where T and P are the tension and linear density of the wire. We impose two boundary conditions on the wire used in our experiments: the wire's deflection is zero at zero-time when the current delta function is applied, and the wire's transverse velocity is determined by the impulse given to it, i.e., its velocity at zero-time is given by

$$dy(z)/dt = I \cdot dt \cdot B(z)/P.$$

To satisfy both of these conditions, we must choose the functions f and g so that $g = -f$ and

$$f'(z) = -I \cdot dt \cdot B(z)/(2 \cdot c \cdot P),$$

where the prime indicates the derivative with respect to the argument. The amplitude, y(t) of the wire's deflection at $z = 0$ (where the sensor is placed), is then given by

$$y(t) = -c \cdot \int f'(-c \cdot t)dt = \int f'(z)dz = I \cdot dt/(2 \cdot c \cdot P)\int B(z)dz,$$

where the integrals are taken from t equals zero to t and from z equals zero to $c \cdot t$. The angular deflection of an electron beam is proportional to this same integral.

2.2. Step-function excitation

Step-function excitation acts like a series of delta-function excitations separated in time by dt and spread out from time equals zero to t. The effect of the first of this string of delta-functions is given by the expression for y above, and the effect of the nth is given by the same expressions with the limits on the z integral changed to zero to $c \cdot (t - n \cdot dt)$. Adding up all of these contributions generates a second integral so that the final result for an infinitely long step is

$$y(t) = I/(2 \cdot c2 \cdot P) \cdot \int\int B(z)dz \cdot dz_1 ,$$

where the limits on the inner integral are from zero to z_1, and on the outer integral they are from zero to $c \cdot t$. The spatial deflection of an electron beam is proportional to this same double integral.

3. Discussion of the limitations encountered

3.1. The velocity c of the wave on the wire

The wave velocity is given by $c = \sqrt{(F/D)}$, where F is the specific tension in the wire (force per unit area) and D is the wire's volume density. As F is increased up to the yield point YS of the wire, the wave velocity approaches a limit $\sqrt{YS/D}$ that is independent of the wire's diameter. For soft copper wire, this limit is about

16 cm/ms, while for hard tungsten wire, it is about 26 cm/ms. For an especially hard copper beryllium alloy, the limit is 45 cm/ms.

3.2. The wire's sag S

In the expression $S = g \cdot D \cdot L^2/(8 \cdot F)$, g is the acceleration of gravity, and L is the length of the wire. Sag, like wave velocity. does not depend directly on wire diameter if F is increased to the yield point. At this limit, the copper beryllium alloy has a sag of about 0.01 mm in a 1-m length and about 1 mm in a 10-m length.

3.3. The wire's maximum displacement Q at the sensor

Using the expression given above for the wire's deflection, we can evaluate the maximum deflection that will be attained if the field, B, has the normal sinusoidal variation with z (where W is the wiggler's wavelength) and if we have chosen dt to maximize the deflection. We then find

$$Q = C \cdot I \cdot B \cdot W^2/(\pi^3 \cdot F \cdot d^2),$$

where d is the diameter of the wire, and C is a constant of order unity. The value of C depends sinusoidally on the width of the delta-function current pulse, and C equals its maximum value 1 when the width is W/(2 · c); for wider pulses, C decreases until at a width of W/c, it is zero. Normally the width is set equal to about one tenth of W/c to provide a reasonably large deflection at the sensor with a reasonably linear response to different wavelengths. The term C is then equal to 0.3, and the pulse length is about 10 μs. For a copper-alloy wire of 25-μm diameter stressed to the yield point and carrying a current pulse of 10 A for 10 μs, the value of Q is about 0.01 cm.

If the deflection of the wire becomes too small for some reason, the sensor's response will be obscured by noise. The noise may be electronic but more usually is in the form of wire vibrations driven by a noisy environment. The environment likely to be encountered in a real situation is ideal with respect to vibrations. Wigglers are often mounted on stable granite tables in temperature-controlled boxes. The lower limit on vibrational noise is thermal noise—noise that establishes an average energy of kT in each vibrational mode of the wire. If one sums over all modes, one finds that the sum rapidly converges to an rms deflection at the sensor Q_{th}, given approximately by

$$Q_{th} = \sqrt{(10 \cdot k \cdot T \cdot L)/(\pi^3 \cdot d^2 \cdot F)}.$$

For typical values of the parameters, this is a very small deflection (i.e., ~0.01 μm).

3.4. The effect of the wire's stiffness

The wave velocity propagated along a wire can be derived by equating the potential and kinetic energies of the wire. The kinetic energy involves the wire's mass in the usual way and the potential energy is calculated from the wire's tension and the work that is done against it as the wire is stretched by the wave. Waves propagate undistorted in shape because the different Fourier components of the wave all have the same velocity and because the attenuation of these components is small.

The manufacturers of stringed musical instruments depend upon the invariant wave velocity to keep the overtones of their instruments close to being true harmonics of the fundamental. That this is not easy is evident from examinations of the complex nature of the bass strings of a piano, for example, and the majority of the strings of violins and guitars. Analyses of this problem go back to Lord Raleigh, but more modern treatments are available [8].

Keeping the velocity of all waves constant is also one of the real problems with our technique. This dispersion is caused by the stiffness of wires and shows up in our experiments as excessive speed of short wavelengths over long wavelengths. A measurement showing this effect is found in fig. 1, where an approximately square wave was started down a wire and was received by a sensor in the distorted shape shown. One can evaluate the seriousness of this effect. It is not a problem if the shortest wavelength of interest is shifted forward on the wave by a distance significantly less than its own wavelength. If we set this shortest wavelength equal to the wiggler's wavelength, we can reevaluate the potential energy term, discussed above, so that it includes the contribution from the wire's stiffness. We find that the wave velocity now depends upon its wavelength as follows:

$$c = c_0 \cdot [1 + a \cdot M \cdot \pi^2 \cdot d^2/(8 \cdot F \cdot W^2)] \ ,$$

where c_0 is the velocity when we ignore stiffness, M is the elastic (stiffness) modulus of the wire, and a is a constant with a value near unity that depends upon the detailed elastic properties of the material in the wire. If we now impose the requirement mentioned above for the stiffness to be an insignificant effect, we find a restriction on wiggler length L given by

$$L < 8 \cdot W^3 \cdot F/(\pi^2 \cdot a \cdot M \cdot d^2).$$

We have attempted to check the validity of this relationship by performing an experiment that violates it. We threaded a 4-mil (100-µm-diameter) copper wire through a 1-m-long wiggler with W = 2.7 cm, tensioned the wire with a 26-g weight, and passed a delta-function current pulse through it. The relationship above indicates that with these parameters, L < 0.5 m. Thus the deflections that we measure with a wavelength equal to the wiggler's wavelength should arrive at the sensor early, by up to two wiggler wavelengths, with respect to deflections of a much longer wavelength. The meaning of this statement can be discovered by examining fig.2, the sensor's output for this experiment.

Fig. 2 shows three major bumps at A, B, and C. These bumps are generated by the entrance magnet to the wiggler, the exit magnet, and by the first reflection of the exit magnet off the adjacent bridge. The smaller wiggles between A and B are generated by the 50 or so oscillations in the wiggler field. The regions of special interest are between B and D, where regular oscillations are expected but are not found, and between B and C, where oscillations are not expected but are found. Both anomolies are caused by the dispersion effect. The rapid wiggles around C and D propagate down the wire to the sensor faster than the major bump at B does, moving ahead of it or catching up to it by the time it reaches the sensor by, we estimate from fig. 2, about five wiggle cycles. Our estimate of this advance from the analytical relationship was two wiggles, in reasonably good agreement.

3.5. Other distortions of the wire

We have identified three other potentially limiting wave distortions: attenuation, scattering on inhomogeneities in the wire, and rotations of polarization of the wire's deflection at inhomogeneities. Attenuation can easily be observed; some of it is caused by air friction and some by internal wire losses. It most seriously effects the short wavelengths. In our measurements, it was always less important than dispersion and could be reduced by the same strategies that reduced dispersion. There is a wide difference in the internal attenuation of different materials, but little information is available in the literature to help in their selection. If attenuation ever becomes a serious problem, a painstaking search for a better material may solve the problem.

Scattering on inhomogeneities can be observed as a gradual increase in the background noise level during a measurement. We have generated a wave that was reflected tens of times off the bridges that support the wire. During the tens of milliseconds in which the wave bounced back and forth over the same piece of wire, scattering by inhomogeneities accumulated and generated the noisy background. Annealing the wire eliminated the scattering. Luckily, very strong wire, such as the kind most appropriate for this application, shows little scattering of this kind. Annealing is not a generally useful strategy because it destroys the desirable high-strength properties of most wires.

Rotation of polarization by an inhomogeneity would necessarily generate a reflected wave that would be detected as a kind of scattering. We have not seen any phenomenon that we can associate with polarization rotation and believe that it is unimportant.

4. The effect of the limitations on the wiggler's length

We have identified four problems imposing limits on the length of the wiggler that can be used with this field-measuring technique: wire sag, dispersion, other kinds of wave distortions, and achieving an adequate wire deflection. The limit caused by wire sag is

$$L1 < \sqrt{(8 \cdot F \cdot S)/(g \cdot D)}.$$

The limit caused by dispersion is

$$L2 < (8 \cdot F \cdot W^3)/(\pi^2 \cdot a \cdot M \cdot d^2), \text{ and}$$

the limit caused by thermally induced wire deflections is

$$L3 < I^2 \cdot B^2 \cdot W^4/(4 \cdot \pi^3 \cdot F \cdot d^2 \cdot k \cdot T).$$

The limits caused by other kinds of wire distortion, such as attenuation or scattering, appear to be small and are not understood well enough to be discussed further at this time.

It is clear that to maximize L1 and L2, we need to maximize F and minimize D, d, and M. The term I in the equation for L3 depends upon d as $4 \cdot V/(\pi \cdot R \cdot d^2)$, where R is the wire's resistivity and V is the voltage across it. When this relation is inserted into the last equation we find

$$L3 < [V^2 \cdot B^2 \cdot d^2 \cdot W^4/(64 \cdot \pi \cdot F \cdot k \cdot T \cdot R^2)]^{3/2}.$$

Obviously, L2 is best satisfied with a small value of d, but L3 needs a large value, as well as a small resistivity and a large voltage.

Because the third relationship is not very restrictive, especially if we make V large, we choose to ignore it for the time being and to optomize the first two relationships. This leads to our final choice of large YS and V and small R, D, M, and d.

5. Examples of possible choices for the wire

A good choice of material for the wire that meets the specifications for L might be an alloyed magnesium (low D) or copper (low R) wire. Up to now we have experimented with soft copper or hard tungsten wire because of their availability to us. The properties [9] of these four kinds of wires are listed as follows:

			Alloyed	
Property	**Copper**	**Tungsten**	**ZK 60A Magnesium**	**C 17200 Copper**
D (g/cm^2)	8.9	19.2	1.8	8.3
YS/g (10^6 g/cm^2)	~0.3	3.9	3.0	14.
M/g (10^8 g/cm^2)	10.	33.	4.5	12.
R (10^{-6} Ω-cm)	1.8	5.3	16.	3.

We have experimented with wires having a diameter of 25 μm (0.001 in.) and find them to be very strong and easy to use. With a wire of this diameter, a wiggler wavelength of 3.0 cm, and a maximum allowable sag of 0.01 cm, we find the length limits to be as follows:

			Alloyed	
Limit	**Copper**	**Tungsten**	**Magnesium**	**Copper**
L1 (m)	0.5	1.3	3.7	3.7
L2 (m)	10.5	41.	230.	410.

In every case, the limit on L3 is so large that other considerations concerning the detection of small wire displacements will dominate thermal noise. Discussions of these detector problems are presented in the literature [10] and do not appear to be severe. The order of the limits established above indicates that dispersion (L2 limit) can be avoided for any wiggler now being contemplated, but that sag (L1 limit) is a problem for wigglers even a few meters long.

6. Discussions of the problem areas

6.1. The sag limit

The sag limit can be extended in at least two ways. One strategy is to accept a moderate amount of sag, for example several millimeters. The output of the sensor can then be compared with an ideal waveform that has been calculated so as to include sag. Any deviation from this ideal represents a field error that can be corrected in the usual ways.

We have investigated an alternative strategy that is useful with wigglers of any length. This technique uses levitating coils on the outside of the wiggler to lift the wire and entirely eliminate the sag at the coil locations. The normal steering coils are perfectly situated to provide this service. A moderate dc current is passed through the steering coils, and a similar current is passed through the wire. The spacing of the coils need not be any closer than the values calculated above for L2, but much closer values are easy to obtain. The accuracy required of the currents is moderate and there do not appear to be any stability problems.

The levitating field cannot be turned on when the delta-function current pulse is generated. The timing sequence of the different current pulses becomes rather complex. First, the levitating currents are applied to both the coils and the wire until stable levitation is achieved without sag; second, these currents are briefly turned off; and third, the delta-function current pulse is turned on in the wire to develop the wave. The sensor's output is then analyzed to determine if there are field errors. If there are, the whole sequence of steps is repeated, but this time with coil currents that have been chosen to flatten the field used in step three. Several iterations may be required.

The lengths of stages two and three have allowable upper limits. When the levitating fields are turned off in stage two, the wire begins to fall. It will fall a significant amount, 0.01 cm, in about 5 ms. Thus, the combination of stages two and three should take less than 5 ms and we can easily design equipment to accomplish this.

6.2. The dispersion limit

There are strategies other than using thin, pliant wires to circumvent the problems encountered with dispersion in very long wigglers. The major wiggler problems that one wishes to discover are field errors that have the same sign over many periods of the wiggler. These are the errors that cause the most deflection of the electron beam. Such long-period errors show much less dispersion on the wire than field variations at the wiggler's wavelength. It is easy to emphasize these long-period errors and deemphasize the short period ones by stretching the length of the delta-function pulse to equal W/c (still only a fraction of a millisecond long). Then the short-period variations on the wire are largely canceled and only the long-period ones are left. This process also enhances the magnitude of the long-period signal at the sensor by about a factor of 10.

6.3. The sensitivity limit

To reduce dispersion when using long wigglers, we recommend using a strong, thin wire tensioned close to its breaking point. The deflection of such a wire will be very low. Even though the fundamental thermal limit has imposed no problem in our analyses, the sensor that we currently use will have to be changed to allow low-noise measurements of these deflections. The best way to achieve this, we believe, is to use a powerful, stable, and sharply focused laser source with a suitable low-noise detector.

Another way to increase the sensitivity of the measurements is to raise the voltage across the wire from the 100 V we now use into the kilovolt range. Fortunately the high vacuum conditions found in the wiggler are ideal to sustain such high voltages. We are currently investigating the use of pulse transformers to generate pulses of many tens of kilovolts for this application.

6.4. Interactions of the current pulse with the vacuum tube

The most natural way to connect a pulse generator to the wire is to use the vacuum pipe through which the wire is threaded as the path for the return current. The wire and tube then look electrically like a coaxial transmission line with a high (~500 Ω) characteristic impedance and a high series resistance (the resistance of the wire). With this circuit arrangement, the current through the wire and the return current in the wall settle down to their dc values a fraction of a microsecond after the pulse is applied. There is a problem, however. If the wire is not centered in the tube, the current flowing in the wall will exert a force on the wire moving it towards the center of the tube. For a wire current of 1 A and a displacement of the wire from the tube's axis of 1 mm, the field generated by the wall currents is about 1/5 G—about the same as the earth's field.

If, now, the tube is not connected as the return path for the wire's current but some external connection is used instead, a wall current will initially flow in the tube identical to the current described above. In a fraction of a microsecond the magnetic field generated by the wire's current will diffuse through the wall of the tube (assumed to be stainless steel and 10 mil thick) and will spread out in space outside the tube. Thus for most of the delta-function pulse (about 10 μs long), the walls will carry no current and exert no force on the wire.

When the tube is connected as the return path, the force we have described is usually small enough to be completely ignored. However, when the wire's current is very large, it may be big enough so that it is necessary to disconnect the tube from the return current path.

7. Conclusions

Using very fine wires of the right materials, one can apply the pulsed-wire technique to wigglers that are several meters long without any modifications to the methods that have been tested and work well for short segments. For longer wigglers (5-10 m), wire sag becomes significant so that intermediate levitation coils must be used to support the wire. Levitation coils can be used with a wiggler of any length, but eventually attention must be paid to the accuracy of both the coils' currents and their physical placement. For wigglers longer than a few tens of meters, dispersion and, perhaps, attenuation become important problems that require a careful choice of wire material.

Technical problems requiring more investigation include generating very high-voltage pulses on the wire, achieving a sufficiently high sensitivity for detecting very small wire motions, reducing extraneous wire vibrations, and developing methods for the accurate placement and energizing of the levitating coils.

8. Acknowledgments

Brian Newnam originally suggested this work and encouraged its completion. Thanks also go to James Elliott for continuing helpful discussions.

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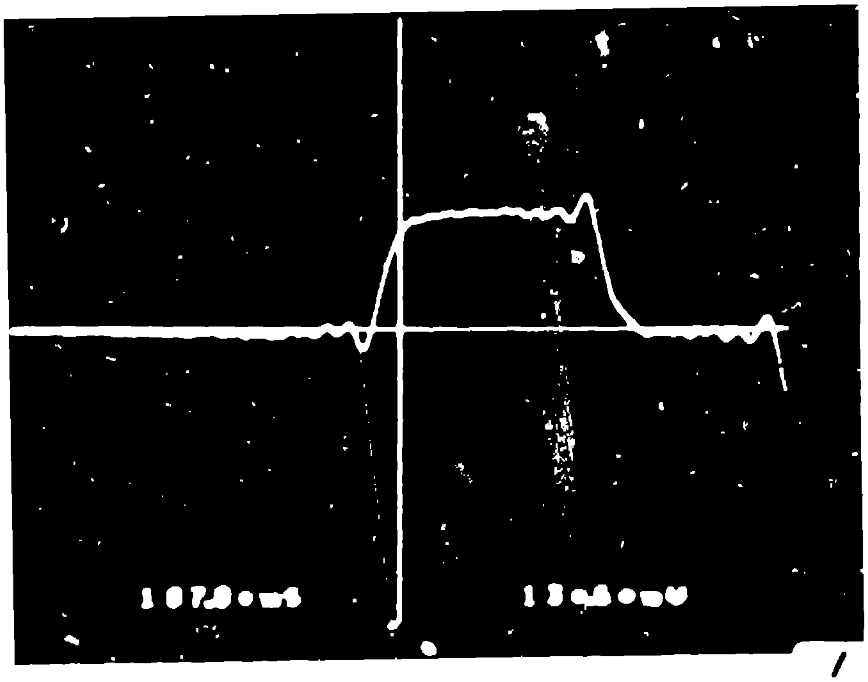
Figure Captions

Fig. 1. Sensor's signal when measuring square wave that is distorted by dispersion effects.

Fig. 2. Sensor's output when measuring 1-m-long wiggler.



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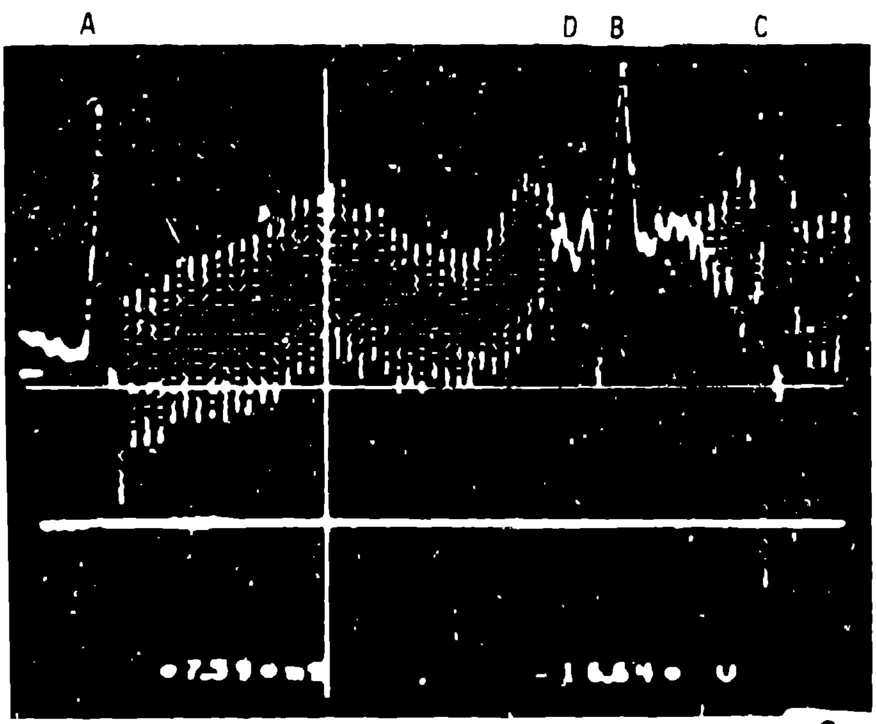

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