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INDUSTRIAL MAGNETIC FIELD MEASUREMENTS

ON

"WARM" SSC DIPOLE MAGNETS

[Report by B. Berkes, SSC/CDG Magnet Div. Meeting, Jan. 27, 1988]

Due to the very large number of SSC dipole magnets, the magnetic field of every tenth magnet only will be measured at cryogenic temperatures. In order to obtain a representative idea of the magnetic field quality of all other magnets as well, magnetic field measurements on "warm" magnets (low current levels) will be made at the manufacturer's site.

The following is an attempt to extract from several possible magnetic field measurement methods those that can meet the requirements for measurements performed by non-skilled people in a rough industrial environment. However, the main assumption for all of the considered mathods is that the field distribution remains the same at low and high field levels.

A. INTRODUCTION

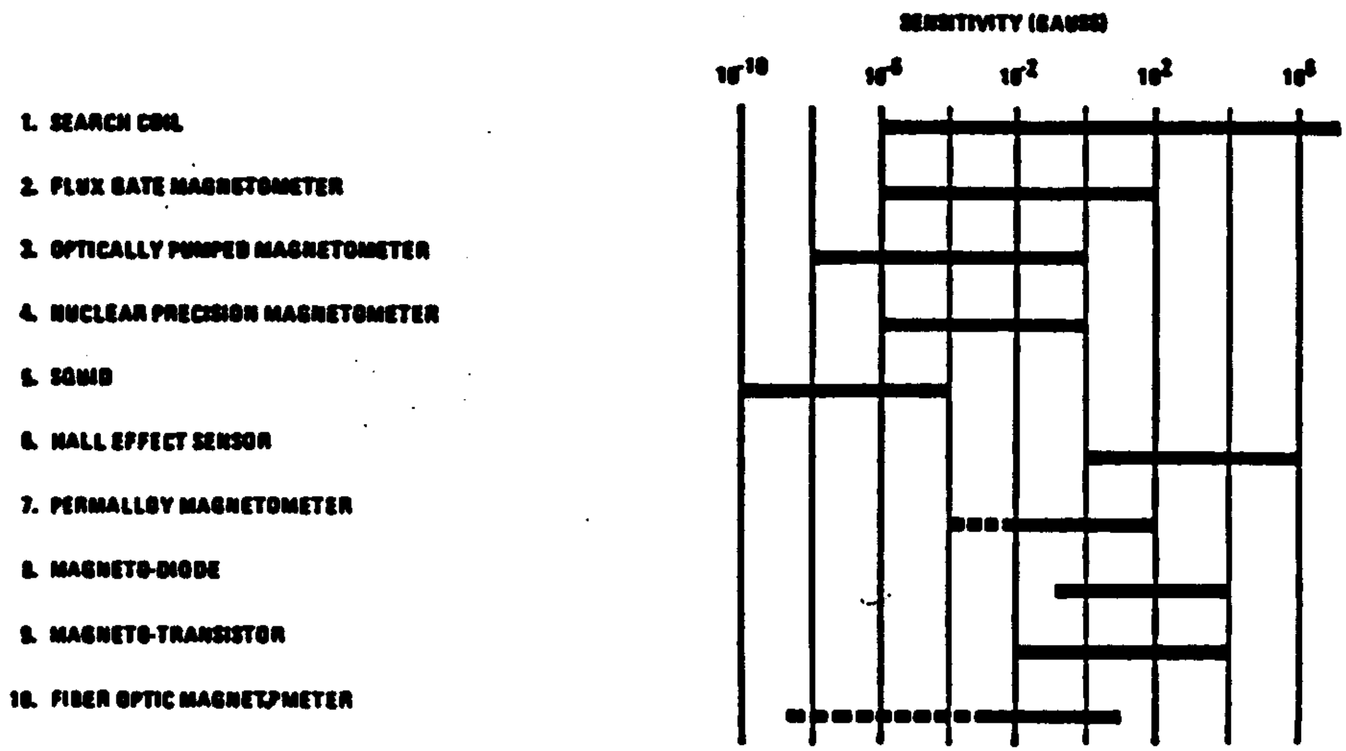
There exist approximately a dozen magnetic field measurement methods, whose suitability for the particular requirements - to measure under rough industrial conditions in a small magnet bore low level magnetic fields (10...20 mT) with high degree of precision - was investigated.

Some of the methods, represented in the table "Magnetic Sensors Comparison" [16],can be excluded in advance from further considerations due to their complexity and volume requirements (SQUID, optically pumped magnetometers). Some others (fluxgate magnetometers [15]) were not considered because of their repercussion on the magnetic field to be measured. Of the remaining methods (sensors), magnetotransistors were not investigated in detail,mainly because of lack of information and time. Instead, ESR precision magnetometers were included into the following considerations.

Comparing different magnetic field sensitive elements, one shall also investigate the influence of the positioning device (sensor holder) on the accuracy of the whole system. For high accuracy/low induction level measurements it is a m u s t to buck-out the main harmonics in order to avoid any excessive (non-realistic) mechanical tolerances. By doing that, only the higher field harmonics in the field would be measured, but the mechanical tolerances for the position of the sensors (radially and azimuthally) would have to be only a few tenth of a millimeter for a measurement accuracy of the order of several 0.01 "units" ([1],[2]).

B. COILS

Coils (of any kind: rotating, stepping, radial, tangential etc.) are, from the magnetic field measurement standpoint of view, certainly the most straightforward devices. However, at very low induction levels and with stringent space restrictions - as it is the case with "warm" SSC dipoles - the use of coils may become difficult, if one has to perform measurements with 0.01 "units" of accuracy. In the following, measurements with radial coils as well as with both d.c. and a.c. dipole magnet magnet excitations, respectively, will be taken into consideration.



Magnetic Sensor Comparison

Advantages

1. linear relation between the voltage induced in the coil and magnetic induction
2. reasonably large sensitivity (except for short coils at d.c. fields)
3. easy to buck-out the main harmonics (dipole)
4. small temperature dependence (small thermal expansion coefficient of the wire)
5. simple and inexpensive instrumentation
6. long lifetime
7. can be used in d.c. and a.c. magnetic fields
8. a.c. measurements with increased sensitivity can be made using lock-in amplifiers
9. nearly direct measurement of the field integral (with long coils)

Disadvantages

1. point-to-point measurements with short coils (to measure higher harmonics with 0.01 "units" of accuracy at a magnet excitation of 15 mT, using for instance a 10 turn stepping coil, one has to resolve 3...30 pVs/sqcm (picovoltseconds per sq. centimeter of the coil area) for each of the 32 measuring steps/revolution; this is at least 2...3 orders of magnitude lower than it can be detected with today's electronic equipment)

2. only a part of the integral field can be measured with a long coil (integral field harmonics must be calculated; otherwise the coil would have to be longer than the magnet itself - constructional problems)

3. arrangement for stepping of the coil holder (increased complexity of the measuring equipment; need more skilled people to handle the measurements)

4. local failures in the magnet construction cannot be detected (very low sensitivity for short coils)

Conclusions/Recommendations

It is practically impossssible to make low level d.c. field measurements with the required accuracy of 0.01 "units", even using long coils.Therefore,a.c. magnet excitation is a must for this type of coil measurements [13]. On the other hand,the precise winding of long thin-wire coils onto the holder can be made only by skilled people (labor cost) and handling of the equipment (long coils) during the measurement procedure at the manufacturer's site requires a fine feeling for delicate apparatus.

In competition with Hall probes, the coil system has the advantage of delivering almost directly the integral values of the higher harmonics. Whether one could make with the described long coil system and a.c. field the measurement procedure faster than with a Hall probe array, has to be investigated in detail.

Recommendable for industrial measurements on "warm" SSC dipole magnets.

C. ELECTRON SPIN RESONANCE MAGNETOMETER

Electron spin resonance (ESR; [9]) is a method similar to NMR. It is especially suitable for very accurate measurements of low magnetic induction levels, using for the resonance detection microvawes (mainly); this means that the signal detecting and processing equipment occupies considerable space.

Advantages

1. measures low B-levels with r.f. (200 MHz equals to approx. 7 mT, with DPPH (diphenyl picryl hydrazyl) as the probe material; [8])
2. point-to-point measurements in principle possible (see par. 4. of disadvantages)

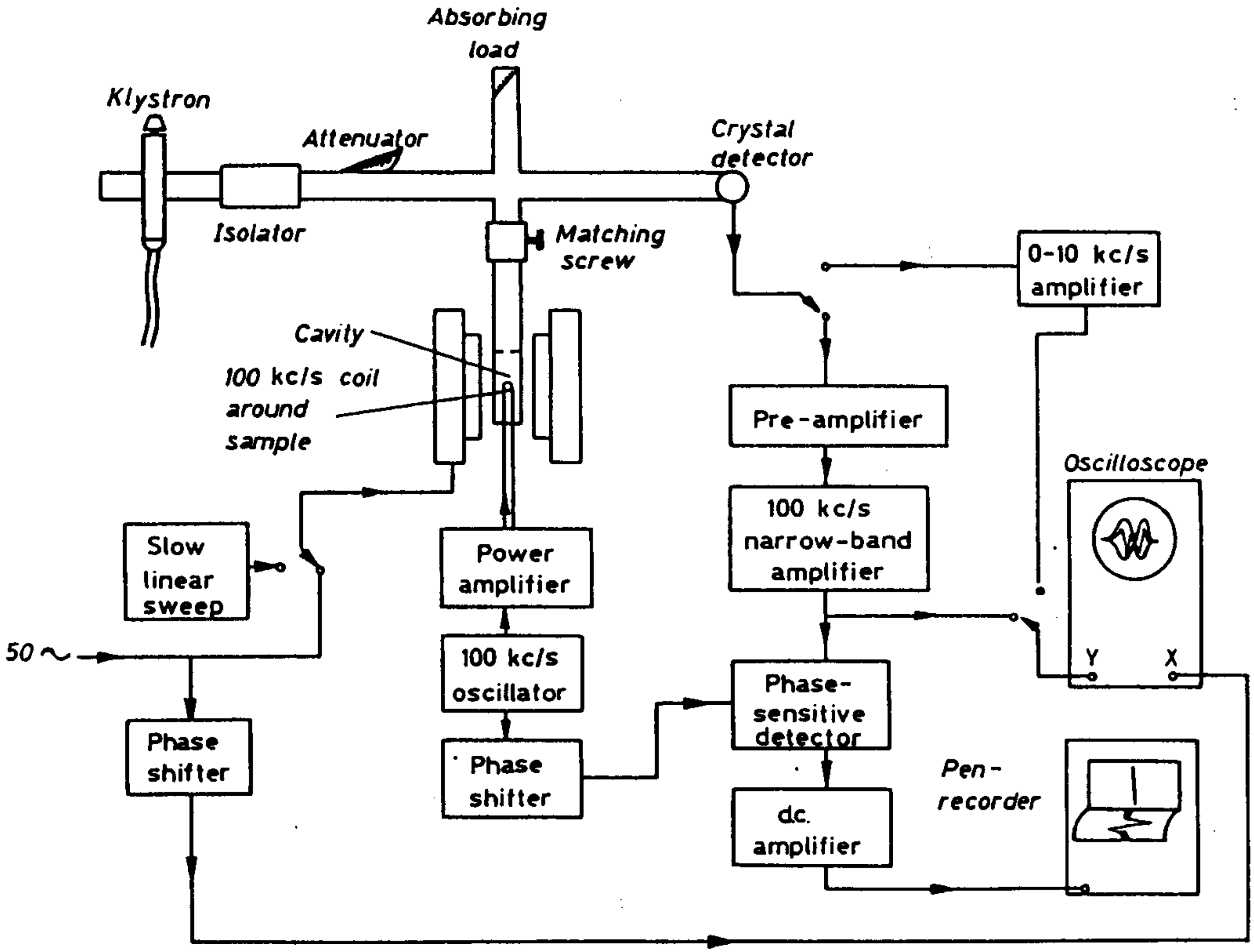
Disadvantages

1. measures only the amplitude
2. needs large samples (a probe-array has no room in the magnet bore; consequence: stepping ESR-probe [8])
3. needs modulation coils (space problem; see also [8], fig. 6)
4. costly equipmnet
5. no integral measurements (measurements on the fly are not possible (see 2.) and therefore long measuring time necessary)

Conclusions/Recommendations

An excellent method to detect small field and/or field changes, but at the price of large probes and complex (?) as well as relatively expensive equipment (instrumentation).

Not practical for use as "the" method to measure the harmonics at 0.01 "units" of accuracy in the small bore of the "warm" SSC magnets.



Block diagram of ESR spectrometer employing 100 kc/s magnetic field modulation

D. FIBER OPTIC MAGNETOMETER

This kind of magnetometers uses two fibers , one beeing coated with a thin layer of NiFe alloy (as an example: 36 : 64 %), and - in conjuction with a light source (laser) and detector (photodiode) - measures the phase difference in the light passing through both fibers, one of which is influenced by the external magnetic field. The magnetostrictive effects in NiFe-layer cause stress in the fiber , which - in turn - is responsible for the phase change of the light.

Advantages

1. extreme sensitivity (down to: 1.0E(-12...1.0E(-13) T at B-levels of 0.01...1.00 mT)

2. point-to-point measurements (with decrease in sensitivity due to the short fiber length, which only can be used for vertical field measurements)

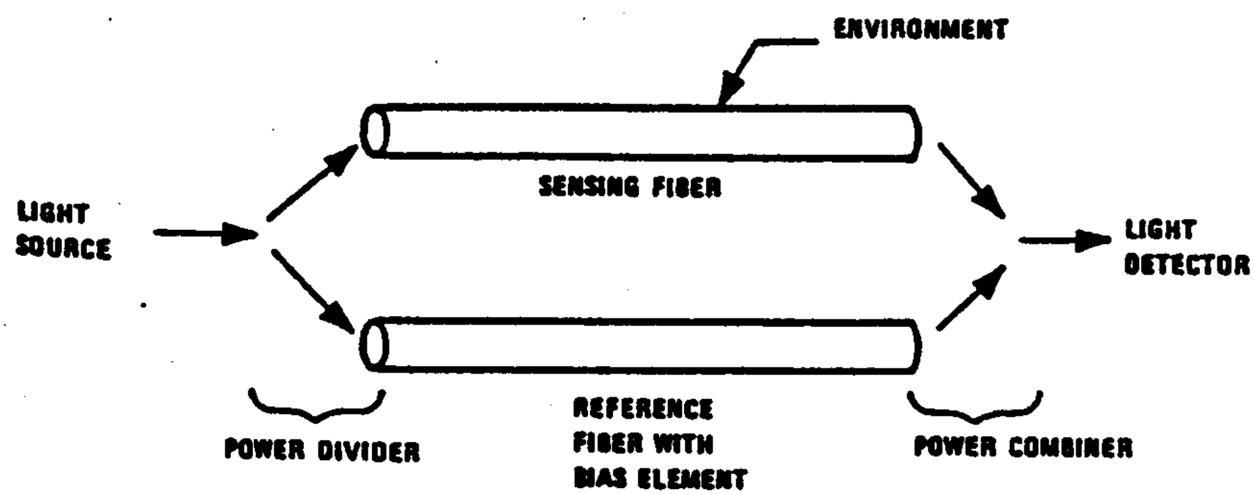
Disadvantages

1. dipole field influenced by NiFe coating
2. sensitivity to external magnetic fields depends on the cosine of the the angle between the fiber and the field direction (zero for fields perpendicular to the fiber)
3. compensation of the dipole field (additional sensor at the holder-axis) possible, but complicated
4. probes are very nonlinear
5. spacious system (d.c. biasing and a.c. modulating field necessary)
6. very extensive and costly instrumentation

Conclusions/Recommendations

In spite of the fact that the system is extremely sensitive , its use as an industrial equipment is m o r e than questionable and would require under any circumstance skilled people to handle the measurement procedure. Even so, the measurements would be very time consuming.

The fiber optic system is not recommendable for low B-level measurements, even in the case that the distortion of the dipole field (see par. 1 of disadvantages) would be negligible.



Basic Fiber Sensor Interferometer

E. HALL PROBES

These semiconductors are four-pole elements ([3],[4]).For high precision magnetic field measurements usually InAs- or GaAs- material is used. Depending on the manufacturing technology, high sensitivities (Hall voltage vs. magnetic induction) can be obtained; this is true especially for ion-implanted GaAs-probes, which will be considered exclusively ([5],[6]).

Advantages:

1. very small dimensions (typ. 3 mm dia and 1 mm thick)
2. large sensitivity (typ. 200 V/(A.T); typ. nom. current: 5 ma)
3. excellent linearity for small B values (typ.0.2% for 0...0.5 T; increasingly better for a bandwidth of +- 10...20 mT only)
4. small TC (typ. -500 ppm/degK)
5. small power consumption (typ. 25 mwatts)
6. good reliability and long lifetime
7. commercially available at very low price (US$ 2.00/pc...7.00/pc)
8. simple and inexpensive instrumentation (power supply and ADC's)
9. can be used in d.c. and a.c magnetic fields
10. point-to-point measurements (local failures in the magnet construction can be detected)
11. due to small dimensions (see 1.) 32 probe array possible
12. measurements in "flying" mode can be made (time savings)

Disadvantages:

1. zero-voltage TC (typ. 1 mikrovolt/degK ; for a magnetic induction level of 15...20 mT and an accuracy of the order of o n l y 1 "unit" (with respect to the dipole) , probe temperature stabilization of +- 0.1...0.2 degC would be necessary)

2. Hall voltage TC (typ. 500 ppm/degK;to make use of the highest available ADC-accuracy, the probes would have to be temp. stabilized (see also par. 1. above)

3. planar Hall effect (measurement errors in the magnet fringe field regions; will not be serious for two reasons: a) the fringe field regions are short with respect to the magnet length, and b) the effect is only about 1 % of the "normal" Hall voltage (GaAs probes) at an induction of 1...2 T and decreases with B-square, whilst the "normal" Hall voltage is a linear function of B)

4. point-to-point measurements (integral harmonics or field length have to be obtained numerically; may not necessarily be a drawback (see advantages, par. 11.))

5. extreme measurement accuracy (accuracy of 0.01 "units" of the dipole is unlikely to be achieved)

6. requires very fast scanners (in order to make use of measurements in "flying" mode; see par. 12 of advantages)

Conclusions/Recommendations

Very likely one of the best and simplest solutions for point-to-point measurements at the accuracy level of one "unit" . For higher accuracy requirements one would have to make use of a sophisticated electronic circuitry [7] in order to increase the Hall probe sensitivity (cost (!)).

In competititon with the coil systems - as the other attractive solution for high accuracy/low level field measurements - one would have to investigate in more detail the technical advantages and drawbacks as well as the manpower and hardware requirements to build the necessary instrumentation and perform the measurements.

Recommendable for industrial measurements on "warm" SSC dipole magnets.

F. MAGNETORESISTORS (FIELD PLATES)

This type of semiconductor is a two-pole element ([3],[4],[5]), whose resistance is approx. a square function of the magnetic induction.The change in the resistance or the voltage deviation of a bridge circuit (with one or two sensors) can be measured.

Advantages:

1. small dimensions (typ. 3 x 2 x 0.5 mm (L x W x T))
2. low TC at low B-levels (200 ppm/degK for a particular doping)
3. no side effects (compared to Hall probes: zero-voltage offset, planar Hall effect)
4. simple to handle
5. commercially available at moderate price
6. simple and inexpensive instrumentation
7. point-to-point measurements (local magnet manufacturing errors or can be detected)

Disadvantages:

1. very low sensitivity at low B-levels (0 at B = 0; typ. 10 ohms/T at B = 15 mT, which corresponds to a change of 0.15 microohms for a measurement accuracy of 0.01 "units")
2. measures only the amplitude of the magnetic induction, regardless of the field direction
3. long term reliability data are not available
4. point-to-point measurements (integral harmonies and field length must be determined numerically;may not be a disadvantage (see advantages, par. 7.))

Conclusions/Recommendations:

Not attractive enough for high accuracy low induction level measurements.

G. NUCLEAR MAGNETIC RESONANCE MAGNETOMETER

This method ([9],[10],[11]) makes use of the spin of the atomic nucleus. By putting the nuclei in an external magnetic field and exposing them simultaneously to an r.f. field,one can observe that at a certain value of the external field energy is absorbed from the r.f. coil (resonance condition); the same condition can be established by changing the coil frequency, whilst the value of the external magnetic field remeins constant.

One can now sweep the r.f. field and so repeatedly cross the resonance condition; with appropriate instrumentation one could than observe the resonance point and determine the value of the external magnetic field, which is directly proportional to the resonant frequency.

Another NMR method uses a pulsed r.f. field (free induction decay or FID); by that,in case of multiple probes, all the nuclei (probes) are simultaneously and not sequentially studied, which is of special advantage in case the probes "see" different field strength ([12],[14]). In what follows, only FID NMR is considered.

Advantages

1. excellent sensitivity for B-levels beyond 0.1 T
2. small size for higher magnetic induction levels (see above)
3. point-to-point measurements possible

Disadvantages

1. measures only the amplitude
2. needs quite homogenous field for proper operation (magnet fringe field regions cannot be measured)
3. very large samples for low B-levels (15 mT) (in order to increase S/N-ratio)
4. dipole compensation (buck-out) questionable (non-realizable mechanical tolerance requirements)

Conclusions/Recommendations

It is unlikely that the multicoil NMR system can be used for measurements at low B-levels due to the probe space requirements and low sensitivity.

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