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Magnetic Field Measurements in Beam Guiding Magnets

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Electromagnets used as beam guiding elements in particle accelerators and colliders require very tight tolerances on their magnetic fields and on their alignment along the particle path. This article describes the methods and equipment used for magnetic measurements in beam transport magnets. Descriptions are given of magnetic resonance techniques, various induction coil methods, Hall generator measurements, the fluxgate magnetometer as well as the recently developed method of beam based alignment. References of historical nature as well as citations of recent work are given. The present commercial availability of the different sensors and associated equipment is indicated. Finally we shall try to analyze possible future needs for developments in those fields.

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ABSTRACT

Electromagnets used as beam guiding elements in particle accelerators and colliders require very tight tolerances on their magnetic fields and on their alignment along the particle path. This article describes the methods and equipment used for magnetic measurements in beam transport magnets. Descriptions are given of magnetic resonance techniques, various induction coil methods, Hall generator measurements, the fluxgate magnetometer as well as the recently developed method of beam based alignment. References of historical nature as well as citations of recent work are given. The present commercial availability of the different sensors and associated equipment is indicated. Finally we shall try to analyze possible future needs for developments in those fields.

1 INTRODUCTION

Before computers became common tools, electromagnets were designed using analytical calculations or by measuring representative voltage maps in electrolytical tanks and resistive sheets. Magnetic measurements on intermediate magnet models and on the final magnets were imperative at that time. Nowadays it has become possible to calculate strength and quality of magnetic fields with an impressive accuracy. However, the best and most direct way to verify that the expected field quality has been reached is to perform magnetic measurements on the finished magnet. It is also the most efficient way of verifying the quality of series produced electromagnets in order to monitor wear of tooling during production. It is curious to note that while most measurement methods have remained virtually unchanged for a very long period, the equipment has been subject to continual development. In the following only the most commonly used methods will be discussed. It is noticeable that these methods are complementary and that a wide variety of the equipment is readily available from industry. For the many other measurement techniques such as the use of the magnetoresistors and the many visual field mapping methods, a more complete discussion can be found in the two classical bibliographical reviews [1,2] and in the proceedings of two recent CERN Accelerator Schools [3,4]. These proceedings contain detailed and important information on the methods described in the following. With their comprehensive collection of articles on magnetic measurements and alignment, of both accelerator and detector magnets, they form a complement to the classical reviews.

2 MEASUREMENT REQUIREMENTS

Electromagnets used as beam guiding elements in particle accelerators or colliders, require very tight tolerances on their magnetic fields and therefore also on their geometric positioning in the accelerator. Construction techniques, measurement equipment and alignment methods must match these requirements. Already at an early stage of the system design, particular

attention must be drawn to definitions of geometry and the future alignment considerations. The length of the magnet is usually small compared to the wavelength of the particle oscillations in the accelerator (betatron oscillations). This means that only the measurements of integrals of the magnetic field and its derivatives along the beam axis are of importance.

Magnetic measurements are important throughout the various stages of an accelerator project: design, construction, installation and operation. The magnetic properties can be characterized as field strength, quality and geometry.

The magnet field strength (or excitation curve) includes that of the hysteresis curve, which is of particular importance in low-field magnets. The field quality, that is the field distribution in space and time, is of importance during the magnet design phase and at a later stage for beam optics studies. The field geometry allows the mechanical reference targets to be defined and determines two critical parameters: the location of the beam axis and the angle of the median plane.

Magnet models are built at the time an accelerator is being studied and designed. At this stage the field quality is the most important parameter and modifications can be made to the magnet design in order to meet the requirements. It is during this phase that the special design features and procedures needed to meet the production requirements are developed.

During the series production of the magnets, the field strength and geometry must be measured in order to monitor field dispersion and confirm or define the position of mechanical reference targets. The dispersion of the measured parameters is of interest both in the case of the field strength and field quality. These series measurements act as a control on the production quality and will detect eventual magnet assembly errors. The results of field geometry measurements are of great importance at the time of magnet installation and alignment in the accelerator. The critical parameter for the alignment of a dipole is its median plane. As a general rule it must be known to an accuracy of 0.1 mrad. A mechanical reference surface or alignment targets are placed in positions, that are easily accessible during installation, alignment and, if possible, for subsequent periodic surveys. In classical steel-core magnets the median plane angle is often defined after a precise mechanical measurement of the gap geometry and its variation along the particle path. This angle can, however, depend on field strength, so it may prove necessary to verify it by magnetic measurements. A tilt of the median plane can be caused by an elastic deformation of the yoke due to magnetic forces, or it may occur due to magnetic saturation of an asymmetric steel core or by influence from surrounding ferromagnetic structures.

In superconducting magnets, where the field geometry is determined mainly by the position of conductors, the tilt of the plane must always be measured. In multipole magnets it is the measurement of the position of the magnetic axis, which is most important. The typical requirement for a quadrupole is

that the position of its axis must be known and represented to an accuracy of 0.1 mm or better.

A problem related to alignment is that of placing magnets in the accelerator according to the dispersion of their measured characteristics. For example, the values of field strength can be used to decide where to locate, or how to combine individual magnets. This sorting procedure can reduce the dispersion of bending strength, thus increase the quality (or reduce the cost) of the accelerator. Many measured magnet parameters will be useful during the commissioning and operation of the accelerator. They will serve to define operational procedures, such as magnetic field cycling or for determining the particle acceleration procedures and for diagnostic purposes. In particular, the value of the total bending strength of the installed magnets can be used for determining the absolute energy of the accelerated particles [5].

3 MEASUREMENT METHODS

3.1. Choice of measurement method

The choice of measurement method depends on several factors. The field strength, homogeneity and variation in time, as well as the required accuracy all need to be considered. Also the number of magnets to be measured can determine the method and equipment to be deployed. As a guide, Fig. 1 shows the accuracy, which can be obtained in an absolute measurement as a function of the field level, using commercially available equipment. One order of magnitude may be gained by improving the methods in the laboratory.

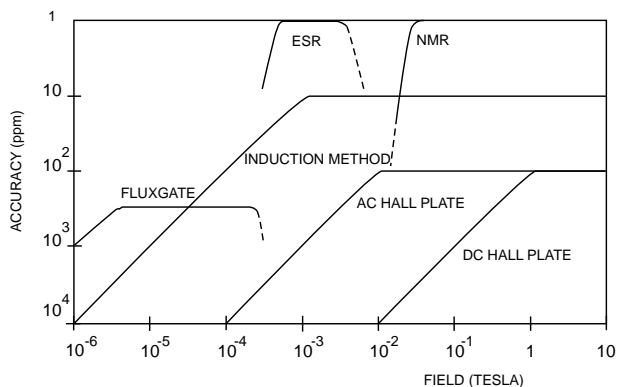


Fig.1 Measurement methods: accuracies and ranges

3.2 Magnetic resonance techniques

The nuclear magnetic resonance (NMR) technique is considered as the primary standard for calibration. It is frequently used, not only for calibration purposes, but also for high precision field mapping. The method was first used in 1938 [6,7] for measurements of the nuclear magnetic moment in molecular beams. A few years later the phenomenon was observed in solids by two independent research teams [8,9]. Since then, the method has become the most important way of measuring magnetic fields with very high precision [10]. Based on an easy and precise frequency measurement it is independent of temperature variations. Commercially available instruments measure fields in the range from .011 T up to 13 T with an accuracy better than 10 ppm. The advantages of the method are its very high accuracy,

its linearity and the static operation of the system. The most important disadvantage is the need for a rather homogeneous field in order to obtain a sufficiently coherent signal. The limited sensitivity and dynamic range also set limits to the suitability of this method. Pulsed NMR measurements have been practiced for various purposes [11,12]. Magnetic resonance imaging (MRI) has been proposed for accelerator magnet measurements [13]. It is a very promising technique, which has proven its quality in other applications. However, the related signal processing requires powerful computing facilities, which were not so readily available in the past.

3.3 The Fluxmeter Method

This method is based on the induction law. It is the oldest of the currently used methods for magnetic measurements, but it can be very precise. It was used by Wilhelm Weber in the middle of the last century [14] when he studied the variations in strength and direction of the earth's magnetic field. Nowadays it has become the most important measurement method for particle accelerator magnets. It is also the most precise method for determining the direction of the magnetic flux lines. The coil geometry is often chosen to suit a particular measurement.

Measurements are performed either by using fixed coils in a dynamic magnetic field, or by moving the coils in a static field. The coil movement may be a rotation through a given angle, a continuous rotation or simply a movement from one position to another. Very high resolution may also be reached in differential fluxmeter measurements using a pair of search coils connected in opposition, with one coil moving and the other fixed, thus compensating fluctuations in the magnet excitation current and providing a much higher sensitivity when examining field quality. The same principle is applied in harmonic coil measurements, but with both coils moving. A wide variety of coil configurations are used, ranging from the simple flip-coil to the complex harmonic coil systems used in fields of cylindrical symmetry.

Induction coils were originally used with ballistic galvanometers and later with more elaborate fluxmeters [15,16]. The measurement accuracy was further improved with the introduction of the classic electronic integrator, the Miller integrator. It remained necessary, however, to employ difference techniques for measurements of high precision [17]. Later, the advent of digital voltmeters made fast absolute measurements possible and the Miller integrator has become the most popular fluxmeter.

In more recent years, a new type of digital fluxmeter has been developed and is now commercially available. It is based on a high quality d.c. amplifier connected to a voltage-to-frequency converter (VFC) and a counter. A true bipolar measurement is provided by a voltage offset on the VFC. Alternating counters are often used in order to measure with continuously moving coils, preventing cumulative errors or to provide instant readings of the integrator. This digital integrator is well adapted to computer control but imposes limits on the rate of change of the flux since the input signal must never exceed the voltage level of the VFC. A suitable integration period must therefore be chosen in order to obtain the necessary resolution.

The coil method is particularly suited for measurements with long coils in particle accelerator magnets [18,19], where the precise measurement of the field integral along the particle trajectory is the main concern. Long rectangular coils were usually employed and are still used in magnets with a wide horizontal aperture and limited gap height. In this case, the geometry of the coil is chosen so as to link with selected field components [20]. The search coil is usually glued on a core made from a mechanically stable material, in order to ensure a constant coil area. Special glass or ceramics with low thermal dilatation are often used as core materials.

The harmonic coil method has now become very popular for use in magnets with circular cylindrical geometry and has been developed since 1954 [21,22,23]. The coil support is usually a rotating cylinder. The induced signal from the rotating coil was often transmitted through slip rings to a frequency selective amplifier (frequency analyzer), thus providing analog harmonic analysis. The principle of the harmonic coil measurement is illustrated in Fig. 2.

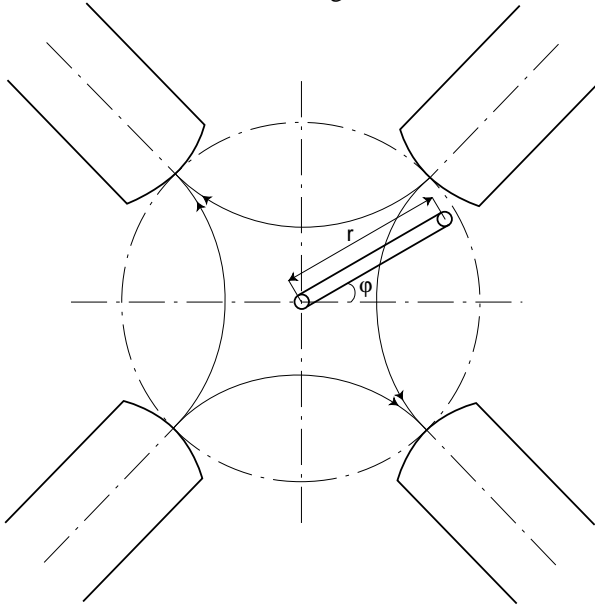


Fig. 2 Harmonic coil measurement

The radial coil extends through the length of the magnet and is rotated around the axis of the magnet. As the coil rotates, it will cut the radial flux lines. A number of flux measurements are done between predefined angles and will permit the precise determination of the strength, quality and geometry of the magnetic field. A Fourier analysis of the measured flux distribution will result in a precise description of the field parameters in terms of the harmonic coefficients a_n , b_n :

$$B_r(r,\varphi) = B_0 \sum_{n=1}^{\infty} \left(\frac{r}{r_0} \right)^{n-1} (b_n \cos n\varphi + a_n \sin n\varphi)$$

where B_0 is the amplitude of the main harmonic and r_0 is the reference radius. In this notation b_1 will describe the normal dipole coefficient, b_2 the normal quadrupole coefficient, etc. The corresponding skew field components are described by the coefficients a_1 , a_2 etc. It should be mentioned that this is the European notation. Those definitions are slightly different in North America. The normal dipole coefficient would be described by a

coefficient b_0 , the normal quadrupole coefficient by a coefficient b_1 , etc.

With the advent of digital integrators and precise angular encoders, the harmonic coil measurement method has improved considerably and is now considered as the best choice for most types of particle accelerator magnets, in particular those designed with cylindrical symmetry. In practice the coil is rotated one full turn in each angular direction while the electronic integrator is triggered at the defined equidistant angles by an angular encoder connected to the axis of the coil. In order to speed up the calculation of the Fourier series, it is an advantage to choose a binary number (e.g. 512) of measurement points. The method provides the advantage of simultaneous measurements of field strength, quality and geometry. The reproducibility and resolution of the flux measurement can be of the order of 100 ppm of the main field component. A compensating coil, connected in series and rotated with the main coil may be used to suppress the main component and thus increase the sensitivity of the system for precise measurements of field quality. More than one order of magnitude may be gained on the measurement of the higher order harmonics in this way.

The field geometry is determined with an angular precision of 0.1 mrad and the magnetic center in multipole magnets may be detected with an impressive accuracy of 0.01 mm [24]. This accuracy is unfortunately often reduced to about 0.1 mm as the mechanical reference point is transferred from the measurement coil to the outside of the magnet itself. Dynamic fields are measured with a static coil linking to selected harmonics [25]. The harmonic coil measurement principle and its related equipment was described in detail in [26]. A thorough description of the general theory including detailed error analysis can be found in [27]. The practical use of the harmonic coil method for large-scale measurements in superconducting magnets was described in [28,29] and more recent developments in [30,31,32,33]. Finally it should be mentioned that complete systems for harmonic coil measurements are now available from industry.

Another induction measurement consists of moving a stretched wire in the magnetic field, thus integrating the flux cut by the wire [34]. It is also possible to measure the flux change while varying the field and keeping the wire in a fixed position. Tungsten is often selected, if the wire cannot be placed in a vertical position. The accuracy is determined by the mechanical positioning of the wire. Sensitivity is limited, but can be improved by using a multi-wire array. This method is well suited to geometry measurements, to the absolute calibration of quadrupole fields and in particular to measurements in strong magnets with very small aperture.

The choice of geometry and method depends on the useful aperture of the magnet. The sensitivity of the fluxmeter method depends on the coil surface and the quality of the integrator. The coil-integrator assembly can be calibrated to an accuracy of a few tens of ppm in a homogeneous magnetic field by reference to a nuclear magnetic resonance probe, but care must be taken not to introduce thermal voltages in the related cables and connectors. It must also be avoided to induce erratic signals from wire loops exposed to magnetic flux changes. Not only the equivalent surface of the search coil must be measured, but also its median plane which

often differs from its geometric plane due to winding imperfections. In the case of long measurement coils, it is important to ensure very tight tolerances on the width of the coil. If the field varies strongly over the length of the coil, it may be necessary to examine the variation of the effective coil width.

The main advantage of search coil techniques is the possibility of a very flexible coil design. The linearity and the wide dynamic range also plays an important role. The technique can be easily adapted to measurements at cryogenic temperatures. After calibration of the coils at liquid nitrogen temperature, only a minor correction has to be applied for use at lower temperatures. On the other hand, the need for relatively large induction coils and their related mechanical apparatus, which is often complex, may be a disadvantage. Furthermore, the measurements in static fields are relatively slow.

3.4 The Hall generator method

E.H.Hall discovered in 1879 that a very thin metal strip immersed in a transverse magnetic field and carrying a current developed a voltage mutually at right angles to the current and field that opposed the Lorentz force on the electrons [35]. In 1910 the first magnetic measurements were performed using this effect [36]. It was, however, only around 1950 that suitable semiconductor materials were developed [37,38,39] and since then the method has been used extensively.

The Hall-generator provides an instant measurement, uses very simple electronic measurement equipment and offers a compact probe, suitable for point measurements. A large selection of this type of gaussmeter is now commercially available. Considerable measurement time may be gained by mounting Hall generators in modular multi-probe arrays and applying multiplexed voltage measurement. Also simultaneous measurements in two or three dimensions may be carried out with suitable probe arrays [40]. The wide dynamic range and the possibility of static operation are other attractive features.

However, several factors set limits on the obtainable accuracy. The most serious is the temperature coefficient of the Hall voltage. Temperature stabilization is usually employed in order to overcome this problem [41], but increases the size of the probe assembly. The temperature coefficient may also be taken into account in the probe calibration by monitoring the temperature during measurements [42]. It depends, however, also on the level of the magnetic field [42], so relatively complex calibration tables are needed. Another complication can be that of the planar Hall effect [43], which makes the measurement of a weak field component normal to the plane of the Hall generator problematic if a strong field component is present parallel to this plane. This effect limits the use in fields of unknown geometry and in particular its use for determination of field geometry. Last but not least is the problem of the non-linearity of the calibration curve, since the Hall coefficient is a function of the field level. The measurement of the Hall voltage sets a limit to the sensitivity and resolution of the measurement, if conventional direct current excitation is applied to the probe. This is mainly caused by thermally induced voltages in cables and connectors. The sensitivity can be improved considerably by application of a.c. excitation [44,45]. A good accuracy at low fields can then be achieved by employing synchronous

detection techniques for the measurement of the Hall voltage [46].

Special Hall generators for use at cryogenic temperatures are commercially available. Although they show a very low temperature coefficient, they unfortunately reveal an additional problem at low temperatures. The so-called "de Haas-Schubnikov effect" [47,48] shows up as a field dependent oscillatory effect of the Hall coefficient, which may become quite significant at high fields, depending on the type of semiconductor used for the Hall generator. But altogether, the Hall generator has proved very useful for measurements at low temperature [49].

Hall generators are calibrated in a magnet in which the field is measured simultaneously using NMR technique. The calibration curve is best represented in the form of a cubic spline function resulting from an interpolation through a sufficient number of calibration points, measured with high precision. This function is defined as a piecewise polynomial of third degree passing through the calibration points such that the derivative of the function is continuous at these points. The coefficients (typically about 60 for the bipolar calibration of a common Hall generator) can be easily stored in a microprocessor device [41,46]. A well designed Hall-probe assembly can be calibrated to a long term accuracy of 100 ppm. By keeping the Hall generator permanently powered, an accuracy better than 30 ppm can be maintained over a period of several months [50].

3.5 The fluxgate magnetometer

The fluxgate magnetometer [51] is based on a thin linear ferromagnetic core on which detection and excitation coils are wound. The method was introduced in the 1930's and was also named "peakingstrip". It is restricted to use with low fields, but has the advantage of offering a linear measurement and is well suited for static operation. As a directional device with very high sensitivity, it is suitable for studies of weak stray fields around magnets. Important developments of this technique have taken place [52,53]. The upper limit of the measurement range is usually of the order of a few tens of mT, but can be extended by applying water cooling to the bias coil. Fluxgate magnetometers with a typical range of 1 mT and a resolution of 1 nT are commercially available from several sources.

3.6 Measurements based on particle beam observation

A method for the precise measurement of the beam position with respect to the magnetic center of quadrupole magnets installed in particle accelerators has been developed over the last decade [54,55]. The procedure consists of modulating the field strength in individual lattice quadrupoles while observing the resulting orbit oscillations. Local d.c. orbit distortions are applied in the search for the magnetic center. This so-called K-modulation provides a perfect knowledge of the location of the particle beam with respect to the center of a quadrupole. In addition, it may provide other very useful observations for operation and adjustment of the accelerator [56]. This is obviously of particular importance for superconducting accelerators [57]. The method may be further improved by synchronous

detection of the oscillation, so that its phase can be identified. The sensitivity of the detection is impressive. Experience from LEP [58] showed that an absolute accuracy of 0.05 mm in both the vertical and horizontal plane could be obtained. Furthermore it was observed that a modulation of the quadrupole field of about 300 ppm could be clearly detected, which means that measurements may be carried out on colliding beams while particle physics experiments are taking place. This measurement method also played an important role for adjustments of the so-called Final Focus Beams [59].

4 FUTURE DEVELOPMENTS

Proven measurement methods and powerful equipment is readily available for most of the measurement tasks related to classical accelerator magnets. It is therefore prudent to examine existing possibilities carefully before launching the development of more exotic measurement methods. The measurement methods described above are complementary and the use of a combination of two or more of these will certainly meet most requirements for classical magnets.

But quite a few problems of precise measurements in superconducting magnets remain unsolved. Bore tubes are getting longer and narrower, thus less and less accessible. The need for very small, remote controlled measurement probes call for progress both in micro-mechanics and electronics. Apart from completely new inventions and techniques we would expect that the progress in micro mechanics could help us to be able to build the smaller and more precise probe assemblies needed in the future.

We may expect an improvement in the flux measurement with the developments of low noise electronics. Also the use of superconducting quantum interference devices (SQUIDS) might in the long run become an interesting alternative as an absolute standard. Hall generators are steadily getting smaller, better and less expensive. The integration of associated micro electronics should improve both quality and efficiency of those measurements.

Actuators for positioning and moving measurement probes play an important role for magnetic measurements. So do precise position sensing devices and gravitational sensors. Further development of very small actuators and sensors for use in cryogenic environments and in high magnetic fields is therefore expected.

The use of laser beams and position detecting diodes [60] has now replaced the classical alignment methods based on telescopes and optical targets. This considerably improves accuracy and measurement speed, both when the reference targets are placed on the magnets and the magnets are installed in the accelerator. We would expect even further progress in this field with the advent of photogrammetry and laser tracking devices.

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