MAGNETIC FIELDS

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Contents

Summary

This chapter presents a review of the role that magnetic fields play in natural processes as well as in technological and – predominantly – in scientific activities of mankind. Different methods of generation of magnetic fields for scientific research starting with the use of simplest permanent magnets and ending with most sophisticated high explosives are also briefly reviewed. Also depicted are some methods of calculation of magnetic fields although the discussion here has to be limited to very introductory level. Finally, basic methods of measurements of magnetic properties are also subjected to a

brief analysis as measurements must necessarily support calculations (and *vice versa* as both are not quite perfect).

1. Introduction . Magnetic fields in Nature, in Science and in Technology

Magnetic fields are quite abundant in Nature. Their role in various natural processes ranges from predominant influence to just an innocent or neutral presence. In some instances that role is completely understood by modern science, in some others, however, it still lies on the margin of mystery in spite of ages of observations and research (the origin of the Earth's magnetic field is an example of such a long standing mystery).

Weak magnetic fields fill the whole outer space penetrating between stars and galaxies driven by streams of ionized matter (being "frozen" into the highly conducting media). Though very weak and very far from the Earth indeed, those fields nevertheless do slightly influence our environment and living conditions. They cause the total randomization of cosmic rays trajectories hiding thus the original sources of cosmic radiation that consequently strikes the Earth uniformly from every direction. Moreover, perturbations in nearby cosmic plasma slightly modulate the cosmic rays flux reaching our planet so that small fluctuations of this flux can be observed. Galactic fields with the induction values of the order of 10^{-6} to 10^{-5} Oe do lead to the weak orientation of interstellar dust particles that consequently causes small polarization of the light passing from distant stars. This polarization can be detected by Earth observers so that the magnetic fields can be measured and even mapped. Another agent reporting the presence of distant magnetic fields is represented by radio waves sent by charged particle spiraling through space. The intensity, frequency and polarization of this *synchrotron* radiation also bring much valuable information on the conditions in some of the most remote corners of the Universe.

Magnetic fields usually manifest in stars (some star species with fields surpassing even 20 kOe are referred to as magnetic) although in regular quiet stars (like our Sun) they are not very intense. On the quiet surface of the Sun 100 Oe might be considered as maximum value. Near solar spots, however, the intensity can easily reach 2000 – 3000 Oe.

The strongest fields ever detected can be produced by some stars undergoing the so called collapse. Prior to that dramatic end the star may not be remarkable in any respect at least as it concerns its magnetic characteristics. When the star eventually dies, however, and collapses into a tiny neutron star the compressed weak stellar magnetic fields increase many orders of magnitude reaching intensities of the order of 10^{12} Oe hardly even imaginable in other circumstances (let alone the possibility of reproducing such fields in our laboratories). Such strong fields cause a lot of very specific effects (e.g. they *produce matter* in the form of electron-positron pairs) and they determine the very nature of star's radiation into outer space (the exact mechanics of which though still quite obscure, that radiation permitting us to observe those exotic stars, otherwise termed pulsars).

Magnetic fields, though rather weak are present on Earth too, and these were for long used in navigation only quite recently being substituted by much more sophisticated means. The intensity of Earth's magnetic field is at its maximum near magnetic poles (not far from geographic ones) where it is roughly equal to 0.5 Oe. Such fields, however weak, were able to magnetize some rocks, and magnetization of Earth's rocks as formed in different geological environments could then be preserved and deciphered in our laboratories to testify the evolution of the Earth geological appearance. Thus rock magnetization was, particularly, exploited to reveal the spreading of the ocean's floor and drift of continents finally confirming the once extravagant Wegener's ideas of South American continent splitting from Africa. It led at the same time to the discovery of quite unexpected abrupt (in geological time scale) changes in the Earth's magnetic field amounting to the complete reversal of its direction. The nature of such changes as well as the nature of the mechanism (so called "Earth dynamo") giving rise to the existence of that field proper (to put it once again) is quite obscure. It was sometimes stated by biologists that the eventual loss of Earth's magnetic field during these reversals could have lead to substantial peaks in cosmic rays flux reaching the Earth's surface and, subsequently, to surges in the rate of mutation among living species (including now very popular poor dinosaurs).

The Earth's magnetic field protrudes far into the outer interplanetary space where it is strongly deformed by the flux of solar wind creating the complicated structure of *Earth's magnetosphere*. Abrupt changes in solar magnetic fields produced by solar flares reach the Earth's magnetosphere with solar wind and lead to magnetic storms, polar flares and eventual disturbances in short wave propagation. Associated with these events are also sudden rises in the flux of solar cosmic rays. This component of the cosmic radiation is characterized by very moderate energies and never penetrate Earth's atmosphere nor reach the Earth's surface. It can lead, however, to the pronounced increase of radiation risks experienced by astronauts while in orbital missions.

Little is known with certainty about the influence of magnetic fields on living species though some mysterious powers from the very beginning were ascribed to magnetism (magnetize still means mesmerize or hypnotize in some languages and magnet or *aimant* is the same as lover in French. Electricity in its turn also was thought of at first as a kind of an elusive animal). Pigeons supposedly use somehow Earth's magnetic field for their navigating purposes and they can be confused by local disturbances such as those produced by powerful radio transmitters. The nature of their magnetic compass is still quite obscure. Some people are frequently thought to be influenced by magnetic disturbances and certain meteorological forecasts include data on "bad" magnetic days. To refine this hypothetical magnetic sensitivity from accompanying changes in other weather factors needs more sophisticated investigation. Wearing magnetic bracelets especially by people with hypertension seems to be rather popular though here too the actual effect (if any) can be strongly masked by much more primitive mechanisms. It is worthwhile noting that before Apollo astronauts reached the Moon a special team was engaged in studying the possible influence of simulated Moon's magnetic field (which is much closer to zero than that of the Earth) on future astronauts' health for fear of eventual discomfort or even more dangerous manifestations. The results were certainly negative and so very encouraging. (It should be stressed, however, that contrary to static or slowly changing fields the use of AC (RF or UHF) fields in medicine relies on quite sound foundations and is supported by a vast experience. The underlying mechanisms are associated not with magnetic fields proper but rather with electric fields and electric currents and with dissipation of heat in body's tissues).

Apart from those in the natural environment, magnetic fields are quite abundant in every aspect of human activity, be it technology, communication, science and now even medical diagnostics. Depending on the application, the role of magnetic fields varies once again from innocent or not quite neutral presence, as they do accompany electric currents or annoying and so undesirable biasing of different electric circuits to the principal means of transformation of one form of energy to another (as in electrical engineering) or of one form of presentation of information to a different form (as in communication, computer science and electronics). In some military applications magnetic fields are still used for very specific purposes (e.g. to trigger anti ship mines) and so are subject of intense search and concealment. In majority of applications in general, the use of magnetic fields calls for their detection and/or for more or less accurate measurement. As magnetic field is very intrinsically connected with its electric counterpart and as it influences a lot of other physical phenomena and physical properties of matter the means of measurement are not much less numerous and various in nature as their applications.

It can be noted as sheer curiosity that in contrast to magnetic fields their electric counterpart or companion (together they form a tensor construction in the science of electrodynamics) though no less abundant plays more modest role at least as it concerns the practical use of fields (aside from just driving electric currents) and their measurements. Moreover, due to relatively easy access to free electric charges static electric fields (assisted by the atmospheric moisture and a lot of anti static appliances) tend to be neutralized and so are much more elusive from direct and precise measurements. The absence of free magnetic charge (of so called magnetic monopole postulated theoretically but not as yet discovered), permits us, furthermore, to build up magnetic fields that are much more intense than electric fields. Thus, fields of the order of 10 kA/cm (or 10 kOe) that are quite regularly used in electric motors, transformers, etc. are equal in corresponding units to electric fields of the order of 3MV/cm which (in static form) are far beyond the reach of any physical laboratory. Otherwise, the maximum electric field that can exist in the dry air prior to the electric breakdown should not exceed 30 kV/cm, which corresponds to a rather modest magnetic field of 100 Oe. The practical consequence is that all our electric motors are essentially magnetic ones as they all do exploit forces produced by magnetic fields. An additional testimony of this situation can be found in the absence of proper names for the units of electric field induction or intensity whereas corresponding magnetic units bear the names of such esteemed learned people as Gauss, Oersted and Tesla (the units of magnetic flux being Maxwell and Weber).

2. Generation of Magnetic Fields in Laboratories

Magnetic fields are regularly used in modern science mainly for two general purposes. First, they can be used as an instrument to produce some desirable and known effect on different objects, such as to bend the trajectories of charged particles (e.g. to measure their energies as that in a bubble chamber or to fit the trajectory into the prescribed path as in accelerators, to prevent ionized plasma from uncontrollable spreading, etc.).

Second, they can be used in order to reveal their own influence on different substances, processes and occurrences. The number of different effects that can be brought about by magnetic fields is nearly innumerable and most of them as well as corresponding magnetic units bear the names of very distinguished learned people (such as M. Faraday, P. Curie and A. Einstein to start with). This number, nevertheless, continues to grow and, according to some philosophers, will never cease to grow. Generating magnetic fields of ever growing intensity, however, has become to an extent the goal *per se* for some in the scientific community. Technical difficulties posed by generated fields are appealing to sophisticated scientific minds and the whole arsenal of complicated tools was used to get still higher fields ending with most powerful high explosives. Former Soviet atomic guru A.Sakharov, who once claimed to have reached 27 millions of Oe (this record as it seems, still stands unbeaten) put a proposal to use even the nuclear explosion to compress the magnetic flux still further.

2.1. Permanent Magnets

We will consider here basic methods of generating magnetic fields, limiting ourselves necessarily to a very sketchy presentation of different appropriate devices. The simplest method of producing magnetic fields (which is the oldest known and usually the cheapest) relies on the use of a magnetized material, such as magnetic ore magnetite or hard steel, etc.(the name magnetite that finally determined even the title of the present article was originally associated with Greek province *Magnesia*). This technique is still in wide use not only in everyday life (magnetic clamps, magnetic sealing, etc.) but also in modern technology and in laboratories. Magnetic cores of measuring devices, of dynamic loudspeakers, small electric motors, permanent magnets of traveling wave tube etc. might be very familiar examples.

Materials to be used for such applications are usually termed as magnetically “hard” (and for the most part they turn out to be hard mechanically). They must posses not only the highest residual magnetic induction, B_r , but also high coercive force, or H_c , to withstand the self-demagnetizing effect (see analysis below). The product B_rH_c frequently (though not quite properly) referred to as “magnetic energy” can be used as a measure of permanent magnet material quality. Some examples of properties of such materials can be found in Table1.

Substance	H_c, Oe	B_r, Gs	BH_{max}	Trade name
W-doped steel	60	10000	0.28	
Co-Fe	220	9000	0.92	
Fe-Al-Ni	550	5500	1.25	
Fe-Al-Ni-Co	500	7000	1.51	Alnico
Ba-ferrite	1800	2000	0.9	
Pt-Co	4300	6500	9.5	
Sm-Co5	9500	9000	20	
Nd2-Fe14B	10000	12500	48	Neomax

Table 1. Some characteristics of hard magnetic materials

As older hard magnetic materials usually did posses H_c values that were much lower (in corresponding units, e.g. in Oersted and in Gauss units which are formally equal) than B_r, the additional external yoke must usually be provided along with permanent magnet proper to conduct magnetic flux more effectively (or to get higher resulting field in place where it is needed). Such yokes are usually made from soft iron which is cheaper than the magnet itself and, besides, can be easily machined to any desirable shape (hard permanent magnet alloys are usually mechanically very brittle substances). The resulting geometry of loudspeaker magnetic system can be illustrated on Fig.1. While in earlier designs the permanent magnet was placed in the center of the system, now it usually forms the outer ring-like cylinder. It is worthwhile noting that in some instances modern magnets for which H_c value might even surpass that of B_r allow one to get rid of the yoke completely without substantial loss of the overall efficiency.

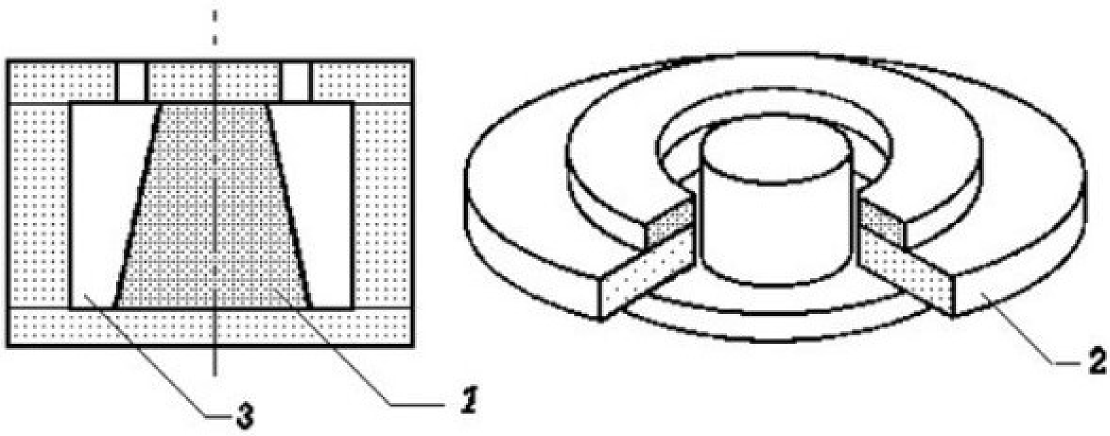

Figure 1. The magnetic system of a dynamic loudspeaker.

2.1.1. Calculation of Magnetic Fields for Permanent Magnets

In many practical applications the value of the field that can be obtained with any magnet system must be known with different degree of precision. While quite rough estimates can suffice in some primitive clamps or toys, many technological applications call for more or less precise calculation of the projected field value. In many cases the exact pattern of field distribution over the operating volume may be of prime importance, like that in nuclear magnetic resonance imaging (MRI) systems or in vacuum electronic devices. In most complicated magnet systems in high energy physics, e.g. in particle accelerators, claims for precision of field distribution in beam tracts can hardly be met, even with the most sophisticated modern technological achievements.

The calculation of the value of the field that one should anticipate to obtain with the aid of permanent magnets is not an easy matter due to their substantially non-linear and irreversible characteristics and it becomes still more complicated if one is interested in the calculation of forces, or of precise field distribution, etc. In the case of a magnet with a properly designed yoke the calculation can be somewhat simplified. The main purpose of the yoke as it was just pointed out is to conduct the magnetic induction flux most effectively, or, being put in terms of Kirchhoff's laws for magnetic circuits, to provide sufficiently low magnetic resistance (*reluctance*) to the flux. As the value of that resistance in case of the yoke with constant cross-section equals simply $L/\mu S$, where S is the cross-sectional area and L – the effective length, for high enough magnetic permeability μ the yoke resistance can be considered to be negligibly small compared with the resistance of the air gap (with permanent magnets the yoke is usually far from saturation). In the absence of magnetizing coils the sum of magnetic potentials as taken along the path of the flux must equal zero, whence $H_eL - H_id = 0$ (d being the width of the air gap and induces e and i denoting as usual external and internal values). If for the sake of simplicity we assume that the cross sections of the permanent magnet and that of the gap are equal and, furthermore, that the flux is concentrated completely inside the yoke, the magnet and the gap, we get $B_i = B_e = H_e$, or $H_i = - B_iL/d$. Thus, the field inside the magnet H_i is opposite to the induction B_i (it is hence sometimes referred to as the demagnetization field) and if the dependence of the induction B_i on the field Hi were known for the given material one would be able to find both H_i and B_i (which in our case equals the operating field value in the gap). The actual dependence of $B(H)$, however, is not usually known with sufficient precision (neither the conditions of the initial magnetization) so that for the first and rather inaccurate approximation one can assume that the linear dependence $B(H)$ does hold:

$B_i/ B_r = 1 + H_i/ H_c$, or, using the above expressions

$$B = B_r /(1 + B_r L/ H_c d)$$

It can be seen from the last formula that for low values of H_c that were characteristic of older magnetic materials (e.g. for simple hard steel) the resulting field can be determined not even by the B_r value, but by the following limiting dependence:

$$B = H_c d/L$$

The evaluation of the fields surrounding permanent magnets without any form of an external yoke is the subject to still more poorly determined factors. We will limit our consideration here by reiterating only one situation well known from the theory, which can be used for some rough evaluations. If the magnetization M of the specimen is fairly uniform and it has the ellipsoidal form, both the magnetic field and the induction inside the specimen are also uniform while (in case the magnetization is parallel to one of the axis of the ellipsoid) the value of the demagnetizing field H_i is proportional to the magnetization $H_i = -4f\pi M$. The proportionality factor f is called the demagnetization factor and its value can be determined given the ratio of the axes of the ellipsoid (see Table 2 for some examples).

L/d	0	1 (Sphere)	2	3.2	16	62	∞	Cylinder ⊥ field
f	1	0.33(3)	0.173	0.1	0.01	0.001	0	0.5

Table 2. Demagnetizing factors for an ellipsoidal specimen

The ellipsoidal magnets though quite popular in high school textbooks are virtually non-existent in any practical device. This concept can be used only as rather poor approximations (especially in zones adjacent to sharp edges) to magnetic rods or discs which, in their turn are now rarely used without additional yokes.

Some problems can also be encountered in performing the initial magnetization of the permanent magnet. It is more advantageous to magnetize it within the assembled system since the demagnetizing field in this case can be much smaller than in the magnet alone. It is also useful to close all air gaps in the magnet system to lower the demagnetization still further (if it is technically possible). The outlay of the system, however, would not readily allow one to place sufficiently large windings that can provide necessary ampere-turns for the magnetization (like that in magnet systems of dynamic loudspeakers). Pulsed mode operation of small windings can sometimes be applied the duration of the current pulse being determined by the acceptable heating of the windings. It should be kept in mind, however, that due to very pronounced skin effect (especially with yoke materials with high magnetic permeability and high electric conductivity) the pulsed field might not penetrate completely into the bulk of the yoke thus magnifying its magnetic resistance. Another possibility is to magnetize the whole magnet system inside the external electromagnet such that some parts of the yoke could be magnetized in reverse direction with respect to normal operating conditions. Since yoke materials are usually magnetically soft this should not lead to any major complications.

Some permanent magnets are still rather extensively used in magnet systems of electromagnetic measuring devices. In precision ammeters (best devices might provide 0.1% precision which is comparable with that of 4-digit solid state digital ammeters) additional and quite severe requirements to the long term stability of the magnetization have to be met. We will not discuss here this rather special application where some procedures of training and 'aging' of permanent magnet materials might be used.

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Biographical Sketch

Kremlev Mark Germanovitch, graduated from the Moscow Institute of Physics and Technology (MIPT) in 1960, and become candidate of physico-mathematical sciences (PhD) in 1966. From 1960 till 1966 he worked at the I.V.Kourchatov Institute for Atomic Energy, and from 1966 up to the present time – at the Institute for High Temperatures, Russian Academy of Sciences. He is Assistant Professor of physics of the Moscow Institute of Physics and Technology. His scientific interests include solid state physics, superconductors and applications of superconductivity He has published more than 50 papers in scientific journals and is the co-author of the book "Stabilization of superconducting systems" published in two editions in Russian (1975, Energy, Moscow, and 1984, Energoatomizdat, Moscow) and translated to English (1977, Plenum Press, N.Y.) and to Chinese. In 1987 (in the former Soviet Union) in a team of nine other scientists he was awarded the State Prize in Physics and Power Engineering.