MAGNETS IN PARTICLE PHYSICS

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Abstract

This review talk introduces a week of specialized lectures on all aspects of magnet design and construction. The programme includes theory, materials, measurements, alignment and some particular applications: it is therefore a very complete coverage of the field and will certainly shed a lot of new light on the subject. Rather than entering into any of these specialized areas, the present lecture will try to present a broad survey of the applications of magnets to particle physics research, and will include a section on the historical developments that led to our present understanding of magnetic phenomena.

1. ACCELERATORS, DETECTORS AND (ELECTRO)MAGNETS

In modern times it is hardly conceivable to design a particle accelerator without resorting to the use of magnets. By "magnets" we almost exclusively mean electromagnets, although permanent magnets have had applications too. In the past these were mainly for vacuum pumps and gauges of various sorts, or for sweeping magnets. It is very encouraging to see that in the last ten years or so permanent magnets have started to be used for focussing (quadrupole) magnetic devices. In fact, one session of this Accelerator School deals with permanent magnets.

Particle **detectors** very often incorporate an analyzing magnet in order to measure the momentum of charged secondary particles by track curvature. The most recent applications in colliding beam experiments have all adopted a solenoidal field geometry coaxial with the (mean) beam direction.

It should be recalled that particle "observation" nowadays is done exclusively by electronic means, therefore the "tracking" information is provided by many small sensitive elements (wires, pads, pixels, fibres etc.) and the reconstruction computer programs make a fit to a continuous curve (circle or helix). The radius of curvature is then a measure of the momentum $p \propto B\rho$.

Reverting to **accelerators**, magnets are ubiquitous: dipoles for trajectory curvature of circular orbits, quadrupoles for focussing, sextupoles, octupoles etc. for higher order corrections, fast deflecting magnets for beam injection and extraction etc. Purely electrostatic deflection and focussing for beam orbits have sometimes been used for very special purposes, but even a low energy "electrostatic" accelerator (e.g. a "tandem" Van de Graaff) nowadays always uses magnetic focussing and deflection.

In any case, however, when seen from the moving frame of reference of the particles, electric and magnetic effects become entangled.

In this review we shall make no mention of the accelerating devices ("cavities" or similar resonant structures) which are really the heart of an accelerator, and which operate with electromagnetic fields of high frequency (10^7 to 10^{10} Hz).

2. MAGNETS IN HISTORY

It is rather interesting to consider how the use and the knowledge of magnets have evolved in history.

It is believed that the puzzling properties of the natural ore magnetite ($Fe_3 O_4$) have been known since the most remote antiquity. The fact that a dark "stone" found in certain specific sites could attract pieces of iron must have fascinated our ancestors. Magic properties attached to particular objects or places were the subject of veneration and gave power to the persons who possessed them. "Loadstone", as it was called, and amber were likened to each other, as the attraction of iron filings or of dry dust particles appeared not very different at first sight.

The names for both magnetism and electricity originated in the Greek world; concerning electricity, as is well known, the Greek name for amber was ἤλεκτρον (electron). Two towns (both located in Asia Minor) and one region in Thessaly (northern Greece) carry the name Magnesia and have been variously proposed as the origin of the name for the magic loadstone (*Μαγνήτης λίθος* or "stone of Magnesia"), because natural magnetite of particularly high quality must have been found there. We should remember that, in the old days, some objects which were highly valued for different reasons were carried along the trade routes over enormous distances: this applied to precious stones, to raw amber, to obsidian and flint, and presumably must also have been true for magnetic loadstone.

This digression on a Greek background notwithstanding, we know that the first documented use of natural permanent magnets as direction finders took place in China. As could be expected, the magic stone was kept under tight control by the ruling class (the emperor, the diviners/magicians, the military chiefs) because of the prestige and power attached to it.

Written and archaeological records going back to the Eastern Han dynasty (AD 25-220) describe a " south-controlling spoon" carved out of solid loadstone (the Chinese, as we know, have always been very skilled at fashioning hard stones such as quartz and jade). These spoons rested in equilibrium on hard, smooth tablets (made in bronze or hardwoods), which were presumably rocked in order to free the spoon from friction as much as possible. The tablets were engraved with 15^0 lines, defining 24 main celestial sectors [1,2,3].

Why the spoon shape? Engraved on some tablets was a schematic outline of the Great Bear constellation (the "dipper"), with its characteristic spoon shape, and this appears to be the reason. Moreover, the Great Bear and the spoon share the same character. These spoon compasses were used to trace the outline of new ceremonial buildings and temples, and to position the throne of the emperor for certain occasions, where an orientation precisely due-south was thought to be particularly auspicious (south is the main reference direction in China). Exploratory expeditions on land and military campaigns also used the spoon, which was entrusted to high officials.

Rather strangely, its use for maritime navigation seems to have come later, and it was then in the form of a "south-pointing fish". This showed progress over the massive spoon, because it was a thin magnetized steel plate (shaped like a fish), slightly concave and made to float on water in a bowl. The magnetization was obtained by rubbing it with a loadstone oriented appropriately. Floating "needles" (pieces of steel wire) were also used, flotation being achieved by smearing them with oil or by laying them on pieces of reed. When not in use the fish or the needles were stored in a box next to a piece of magnetite, and elaborate procedures were prescribed for remagnetizing them periodically.

Only the flagship in a fleet carried the compass, the other ships following by sight. Such devices must have been much more sensitive than the spoon (less friction) and more practical to use. Suspensions by silk thread or onto a needle point also came into being soon after, i.e. in the first centuries AD. Korean and Japanese sailors also used similar compasses for navigating in the Far East.

Many centuries passed before the existence of the device was recorded in the Mediterranean. Presumably, Indian and Arabic ships must have possessed it over this long transition period, but the fact is not documented. It may also be argued that such an important, strategic invention was successfully kept secret over a long period. After all, in times much closer to us, the descriptive geometry developed by G. Monge was kept classified because it helped to aim the long range artillery in the Napoleonic wars .....

What seems to be established is that the use of compass-like devices appeared in the literature of several circum-Mediterranean countries from the end of the XII century. The first such mention seems to be a text by Alexander Neckam, of 1190, describing the use of a magnetized needle by sailors. There is a curious poem by Guyot de Provins, dated 1205, which praises "la vertu de la magnette" as used by "li marinier qui se navoient". Among the many references, there is a text by a Persian writer (Muhammad al-Awfi) in AD 1232.

Legend had it that the small maritime republic of Amalfi, in southern Italy, was the "birthplace" of the compass and that the inventor was a certain Flavio Gioia. Dante himself, in the Divina Commedia [4], mentions the compass in a rather matter-of-fact way, and so we may assume that, by the beginning of the XIV century, this instrument had become common around the Mediterranean.

3. TOWARDS A PHYSICAL UNDERSTANDING

For a very long time, and apart from the most readily observed properties of natural magnets (attraction / repulsion, even through obstacles made of various substances; declination and inclination in the earth's field) there was essentially no progress in the understanding of the phenomena.

It was, however, already known to the Chinese that cutting a magnet in two halves would produce two magnets, with opposite-sign poles at the fracture surface. The magnetic attraction was attributed to a "breathing-in" action, or to the creation of a vacuum between magnet and iron filings. A parallel was drawn with male-female sexual attraction.

The Greek philosophers made essentially no contribution to the subject, apart from proposing some obvious, animistic comparisons. In Roman times Lucretius included magnetic phenomena in his description of nature's workings, but again, no new insight was provided.

In more recent times, well after the appearance of the compass in the western world in the XII century, the first serious study was done by William Gilbert, who, in 1600, published his work *De magnete magneticisque corporibus et de magno magnete tellure*. He identified and studied the poles (by observing lines of iron filings) on a sphere of magnetite, which he called "terrella", and is credited with likening the earth to a giant magnet. To him is also attributed the first use of the word "electric" (*vis electrica*).

However, after Gilbert, two centuries passed before any real significant progress was made. It is strange that in the times of Galileo and Newton these puzzling magnetic phenomena found no serious investigator. An account of how things stood in the second half of the XVIII century can be obtained from the Encyclopaedias and Scientific Dictionaries published in those days [5, 6], which we take as being the "*nec plus ultra*" of contemporary scientific and technical knowledge. The realm of magnetism (and to a lesser extent, of electricity) fares rather badly in comparison with other branches which were already highly developed (celestial mechanics, astronomical observations, calculus, and even anatomy).

The sciences which were in the most appalling state were Chemistry and Magnetism. Concerning the latter, one finds explanations based on magnetic "virtue", "fluid" or "matter"; descriptions of little round particles, themselves endowed with north and south poles, which stream out of long, narrow pores parallel to the magnet axis and which form a vortex around the magnet; or of screw-shaped particles, of opposite handedness, which traverse the magnet along screw-shaped channels etc., etc. On top of it all, the reasoning that accompanies these descriptions is of the kind that can "explain everything and the opposite of everything".

On the other hand, the Encyclopaedia of Diderot-D'Alembert (1780 edition) carries a couple of interesting statements, namely:

- several experiments made by John Michell lead us to believe that the attractive / repulsive forces vary inversely with the square of the distance involved
- as to the hypothetical "magnetic matter" (said to be "thin, different from air") "...we ignore absolutely the way in which it acts. And another equally difficult question is to know whether there is any relation between the causes of magnetism and of electricity..."

It only took a few more years before Charles Augustin Coulomb firmly established (in 1785) the inverse square law. As for the other question, the breakthrough was made by Hans Christian Œrsted in 1820. A professor of physics at Copenhagen, he had the habit of preparing in advance some experimental demonstrations for his students [7]. For some time he had been interested in the effect of thunderstorms on the magnetic needle, and believed that heat, electricity and light must have been connected to one another and hence have played a rôle in the phenomenon.

He therefore heated a thin platinum wire with an electric current from a pile (a recent invention) and observed that a magnetized needle, initially set parallel to the wire, was deflected sideways. He realized immediately that this was a new phenomenon, not yet ripe for his physics class demonstration. In his own words, "my former conviction of the identity of electric and magnetic forces developed with new clarity". When he returned to continue the experiment, he correctly attributed the effect to the current and not to the heat (or to the light), and published his discovery in Latin in a paper called *Experimenta circa effectum conflictus electrici in acum magneticam.*

We should recall here that the study of electricity had enjoyed an advantage over magnetism for several decades. Electrostatic generators and condensers had allowed a considerable amount of experimental work over many aspects, not only of static electricity, but also of currents flowing in conductors [8]. The names of Charles Dufay, Abbé Jean-Antoine Nollet, Giovanni Battista Beccaria, Louis Guillaume Le Monnier, Henry Cavendish and Benjamin Franklin are all associated with many important advancements. This early programme included even a first, rudimentary estimate of the propagation velocity of electricity in a circuit composed of many monks (!) forming a chain and receiving an electric shock: their apparently simultaneous jolts permitted a lower limit of about 7400 m/s to the propagation velocity to be established in 1746.

It was, however, the invention of the electrochemical pile by Alessandro Volta in 1799 that opened the way to quantitative, reproducible experiments using currents much higher than had been possible beforehand. A lot of this high current, electrical work was on the electric arc and the electrochemical phenomena, and it contributed enormously to the advancement of chemistry.

Œrsted's paper immediately became known in Europe's scientific circles, where his experiments were repeated. One such demonstration, by Charles Gaspard De la Rive, took place in Geneva [9] during the summer of that same year, 1820. Dominique-François Arago attended the demonstration, and shortly afterwards communicated it to the Academy of Sciences in Paris. The date was September 11, 1820 and in the audience was a very capable mathematical physicist, and professor at the École Polytechnique, André-Marie Ampère who, within one week formulated the laws of electromagnetism. Thus, a field of physics that had remained dormant for such a long time, very rapidly joined the mainstream of knowledge.

The pace of fundamental developments continued to accelerate. Shortly afterwards (in 1829) Joseph Henry discovered self-induction, and Michael Faraday carried out his important work on electromagnetic induction in 1831. Electric transformers were soon built, followed by dynamos and motors. Electricity was no longer a curiosity for the cabinets of the "savants", but was finding its way into the workshop and into the home. A new electrical industry grew very rapidly with power stations and transmission lines starting to dot the landscape.

I shall conclude this historical digression by recalling the contribution of a scientific giant, James Clerk Maxwell, who in 1864 published his famous equations, uniting in a single, coherent synthesis electricity and magnetism, with their static and dynamic aspects, and predicting the phenomenon of electromagnetic wave propagation with a well defined velocity. The experiments of Heinrich Hertz, Augusto Righi, and Guglielmo Marconi opened the way to our present world of instant, global communication.

4. MAGNET DESIGN: THE GENERAL PROBLEM

When approached from a very general point of view, designing a given magnetic field configuration should be a straightforward problem. The Maxwell equations are of course the starting point, as they relate the space- and time-derivatives of magnetic and electric fields with the distribution of charges and currents producing them.

The equations, as presently shown to be valid, lack symmetry between electric and magnetic charges and, as is well known, free magnetic charges (magnetic monopoles) have not been found experimentally, in spite of numerous, very ingenious attempts. This situation has to do with the observation that a broken bar magnet gives two new magnets, and this same fact has been used to explain, by analogy, the confinement of quarks inside the nucleon (try to pull a single quark out, and when you have spent enough energy in the process, all you obtain are two new quarks). The search for monopoles, however, is continuing and it is not completely excluded that, some day, we may be compelled to complete the famous set of equations.

These considerations, however, should not concern us for the present discussion. Given a certain configuration of electric currents in space, one can calculate the magnetic field components, and, vice-versa, a desired magnetic field shape determines, in principle, the configuration of required currents. This simple situation is found nowadays in the design of iron-less superconducting magnets, and the well known "cos θ" design of superconducting dipoles is the best illustration (Fig. 1).

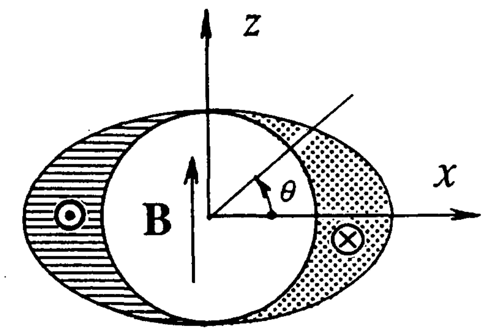


Fig. 1 Pure dipole field (cosθ current distribution)

In fact, it can be shown analytically [10,11] that some theoretical current distributions give exact solutions to the most important, simple field shapes useful in accelerators. A "generalized cos θ" distribution, with an infinitely thin current sheet flowing along the surface of a cylinder of radius a, in a direction parallel to the axis and varying with angle θ as:

$$I(\theta) = I_0 \cos(m\,\theta)$$

generates pure multipoles of order m:

$m = 1$	dipole	$B_z = -\mu_0 \dfrac{I_0}{2a}$	$B_x = 0$
$m = 2$	quadrupole	$B_z = -\mu_0 \dfrac{I_0\, x}{2a^2}$	$B_x = -\mu_0 \dfrac{I_0\, z}{2a^2}$
$m = 3$	sextupole	$B_z = -\mu_0 \dfrac{I_0}{2a^3}(x^2 - z^2)$	$B_x = -\mu_0 \dfrac{I_0}{a^3}\, x\, z$

In the case of the quadrupole, $B_z \propto x$, and $B_x \propto z$; and therefore charged particles traversing the quadrupolar element along trajectories displaced from the symmetry axis are subjected to transversal forces proportional to the displacement. These are the restoring, "elastic" forces that (subject to sign considerations) assure a harmonic oscillator behaviour.

It should also be noted that $\dfrac{\partial B_z}{\partial x} = \dfrac{\partial B_x}{\partial z}$ as expected.

Other conceptually simple geometries are pairs of intersecting ellipses [10-13], defining domains of constant current densities, which, again in a two-dimensional approach, generate pure dipole or pure quadrupole fields according to the relative orientation of their major axes. In analogous conditions two intersecting circles define a pure dipole field (Fig. 2).

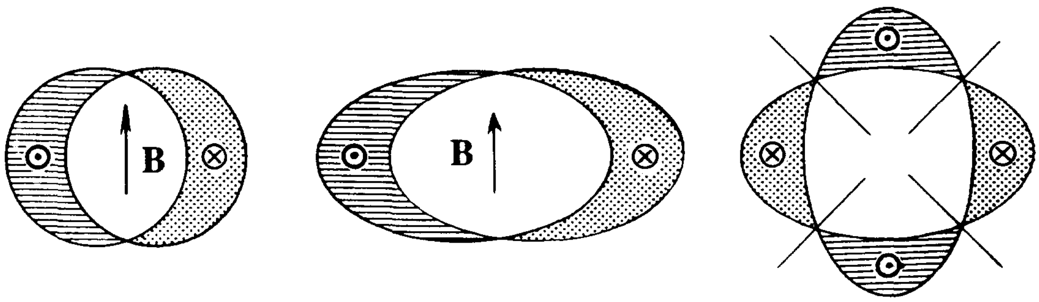


Fig. 2 Pure dipole and quadrupole fields
(constant current density between intersecting circles / ellipses)

Even in these conceptually simple configurations, complications arise when one is led to consider the finite length of the elements. The current-carrying conductors need cross connections at the end of the magnet, and these introduce considerable distortions of the field pattern in their neighbourhood. The local, precise values of the magnetic field components are important to assess the working conditions of superconducting coils, and the integrated values must be known in order to calculate overall bending and focussing power.

5. IRON MAGNETS FOR ACCELERATORS

In practice the simple approach discussed above has been of very limited use to the magnet designer, at least up to recent times. In fact, the field configuration was almost always determined by the iron pole pieces; this had both advantages and disadvantages. On the one hand, the presence of iron permitted useful values of the magnetic flux density (say, up to B = 2 T) to be reached with very modest investments in Ampère-turns for the return path. This also confined the stray flux to the immediate vicinity of the magnet gap, and in special cases, it provided a direct, very particular shaping of the field (especially notable is the case of the quadrupoles, Fig. 3).

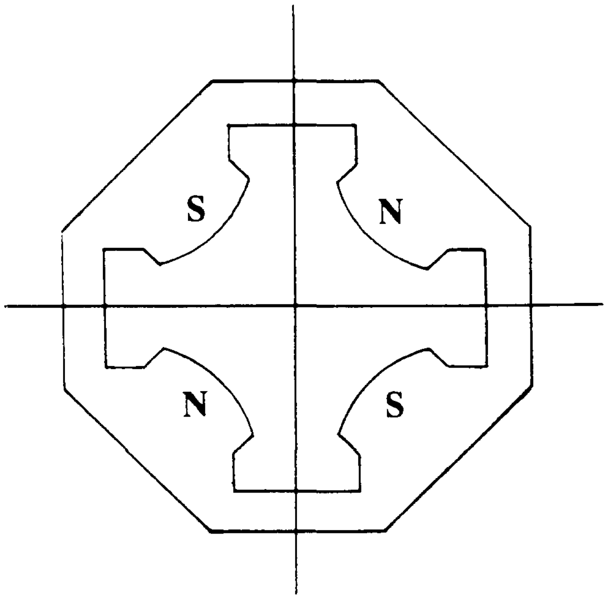


Fig. 3 Typical iron yoke of a quadrupole

On the other hand, numerous drawbacks were found due to the properties of iron: non-linearities, saturation, hysteresis, remanent fields, eddy currents in the case of pulsed fields, etc.

Gradually an art of designing magnets came into existence, and all these difficulties were circumvented, at least within certain limits. Pole faces were shaped in clever ways, shims were added to the sides of the air gap and to the magnet ends, special grades of mild steel were selected, magnetic yokes and poles were made out of laminations, special excitation cycles were devised to minimize hysteresis effects, etc.

The results obtained have been remarkable: for instance, in dipoles it became normal to maintain field non-uniformities to within a few parts in 10^4, at field values of up to about 2T, for magnets ramped in 1 s from 5% to 100% of B_{max}. These values are typical of high-energy proton synchrotrons, for which hundreds of dipole magnets have been manufactured and operated successfully (Fig. 4).

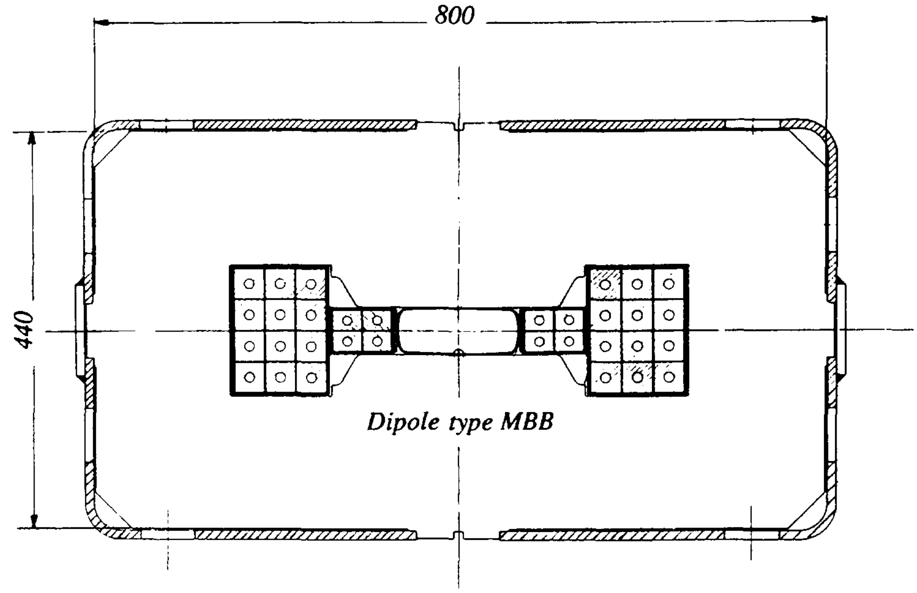


Fig. 4 Dipole of the SPS (one of two types)

For some time now the design of the magnetic circuit has been worked out with the help of computer methods, using the decomposition of the structure into finite elements. To assist the designers, several highly refined programs exist, both two- and three-dimensional, into which one can feed the non-linear characteristics of the iron to be used.

This powerful approach has to a large extent replaced the lengthy and laborious process of proceeding largely by model work, as was still done in the 60's. In fact models now tend to be final versions of the real things to be built, and are mainly used to test technologies and materials, or to demonstrate to manufacturers the feasibility of the design.

Construction techniques, in particular the selection of mild steel grades, the stamping of the laminations, the mixing techniques used to randomize the errors, the assembly, and the measurements have also reached a high level of refinement and reliability. It can be stated that the best end results are in fact obtained with laminated magnets, even in the case of constant field applications; therefore, as soon as the quantity involved justifies it (about ten or more), this tends to be the natural choice.

Some of the most remarkable designs of iron magnets have probably been realized for the spirally-ridged pole pieces of the isochronous cyclotrons (Fig. 5).

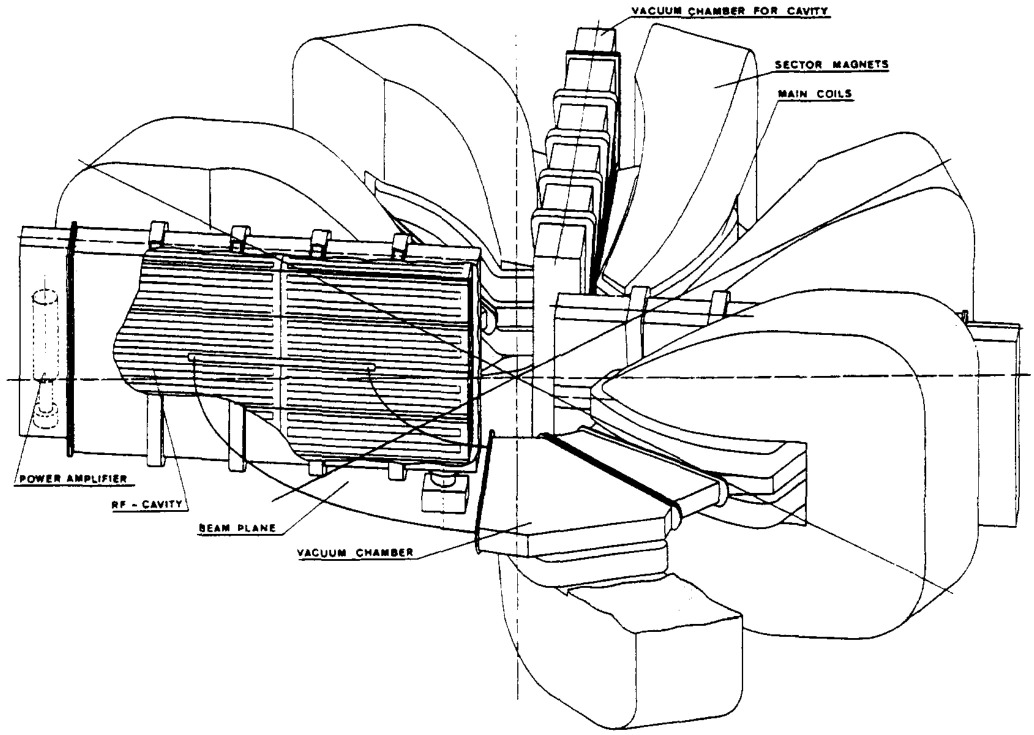


Fig. 5 Isometric view of an isochronous cyclotron (Paul Scherrer Institute)

There is a class of circular accelerators/colliders, of which LEP and the electron ring of HERA are recent examples, which operate with relatively low flux densities (e.g. of the order of 0.2 T or less). The reason for this design choice is the necessity to limit the amount of synchrotron "light" radiated by the circulating electrons and positrons to within a manageable level . The power emitted, P, increases in fact with the fourth power of the particle energy, E, but is inversely proportional to the radius of curvature of the orbit, ρ:

$$P \propto \frac{\gamma^4}{\rho} \quad \text{with } \gamma = \frac{E}{mc^2},$$

mc^2 being the rest energy of the electron or positron, $mc^2 \cong 0.51$ MeV.

The designer is therefore led to adopt the largest possible values for ρ, and hence to operate the dipoles at low flux densities.

For this class of ring, iron magnets remain the natural choice, albeit with ingenious schemes to contain the weight and cost of the iron. For instance, LEP has adopted dipoles made of steel laminations spaced by inert material, i.e. concrete (Fig. 6).

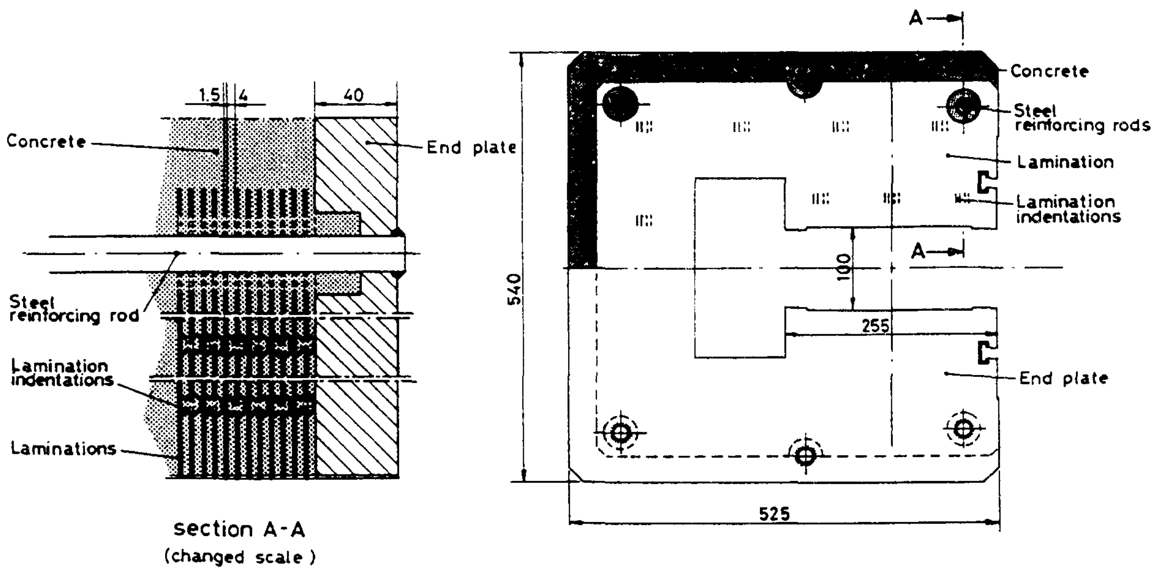


Fig. 6 Steel-concrete dipoles of LEP

At the other end of the range, and by far the most numerous and technically most challenging, are the magnets for accelerators requiring the highest possible values of magnetic field. These are the accelerator/collider rings for beams of protons (and/or antiprotons) and ions of various kinds. Considerations of cost and available sites have in fact pushed the designers to adopt flux densities in excess of 5T. This has only been made possible by the advent of superconducting technology.

6. SUPERCONDUCTING ACCELERATOR MAGNETS

Discovered in 1911 by H. Kamerlingh-Onnes, superconductivity for a long time remained a puzzling, unexplained phenomenon. It was only in the 30's, 40's and early 50's that continuing experimentation uncovered additional facts (e.g. the exclusion of magnetic flux, called the Meissner-Ochsenfeld effect; anomalies in physical parameters, etc.) allowing a gradual interpretation of the phenomenon (F. & H. London, L.D. Landau and V.L. Ginzburg). A satisfactory theory, however, only came in 1957 (J. Bardeen, L.N. Cooper and J.R. Schrieffer – the so-called "BCS theory"), identifying the current carriers as pairs of bound electrons, behaving like bosons and therefore all able to condense at the lowest energy [14, 15].

The passing of the transition temperature manifests itself in discontinuities of the physical parameters (e.g. of the specific heat), which are characteristic of a phase transition of the second order.

Not all materials become superconductors, at least at the lowest temperatures tested so far, and not all superconductors behave in the same way. The complete magnetic flux exclusion (typical of the "type-I superconductors", such as lead and tin) does not hold for another class (called "type-II superconductors"), where gradual flux penetration can take place in the form of quantized "fluxons", i.e. flux bundles anchored to lattice defects and inclusions.

This second type of superconductor includes all the alloys and compounds used to fabricate conductors for magnets, namely the most important of all, the alloy niobium-titanium and, to a lesser extent, the compound Nb_3Sn. The fact that the fluxons are anchored ("pinned") to specific points of the lattice allows these materials to reach very high values of the magnetic field, until an "upper critical field", H_{c2}, is reached, when the transition superconducting to normal (known as "quench") takes place.

We shall not discuss here the more recent kinds of ceramic superconducting materials (called "High-T_c superconductors") which are the subject of much investigation, tending to elucidate this particular new mechanism of superconductivity. Their applications for magnets may well become important in the future, but for the time being this is not the case.

The practical design of modern superconducting magnets for accelerators (dipoles, quadrupoles, higher multipoles) has reverted to the simple and elegant configurations discussed earlier, i.e. to current distributions located around a cylindrical aperture. Of course, the current layer cannot be infinitely thin, nor its current density vary in a continuous way as required by the "cos $m\theta$" law. These difficulties have been overcome by adopting sector-shaped current domains, in concentric layers, separated by inert spacers (Fig. 7) [16].

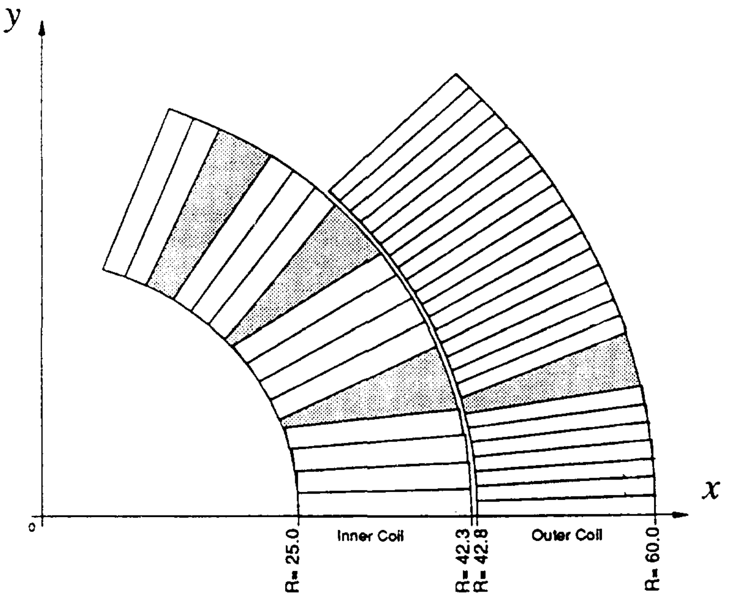


Fig. 7 Arrangement of active and passive sectors in a superconducting dipole

Hundreds of superconducting magnets have been manufactured and operated in recent years (Tevatron ring at Fermilab, Chicago; proton ring of HERA at DESY, Hamburg) and have shown the soundness of the approach.

Much greater quantities and more stringent characteristics will be needed for the very large hadron colliders being proposed at present. These are the SSC in the state of Texas, U.S.A., which will require 8 500 dipoles operating at 6.6 T, and the LHC to be built at CERN.

We shall summarize here the most interesting aspects of this latter project [17]. In order to reach the highest collision energy (about 2 x 8 TeV) and thereby maximize the research capabilities of the machine to be installed in the existing LEP tunnel, it has been decided to aim at a dipole field of 10 T. Superconducting windings of NbTi/Cu composite cable with filaments of 5 μm, cooled to 1.8 K by a pressurized bath of superfluid helium, will be used.

The two apertures for the counter-rotating proton beams will be housed in combined magnetic structures, having the advantage of great compactness and economy (Fig. 8). The number of twin-aperture main dipoles (9 m long) and quadrupoles (3 m long) will be 1 792 and

392 respectively. Altogether 31 000 tonnes of "cold mass" will have to be cooled, by eight very refined refrigeration plants totalling more than 50 000 kg of helium. Field uniformity in the dipoles is an important constraint, which means that the unwanted multipole components, normal and skew, are to be kept to within well defined limits. The techniques used to measure these terms and to evaluate their influence on the stability of the stored beams have themselves reached a very high level of specialization.

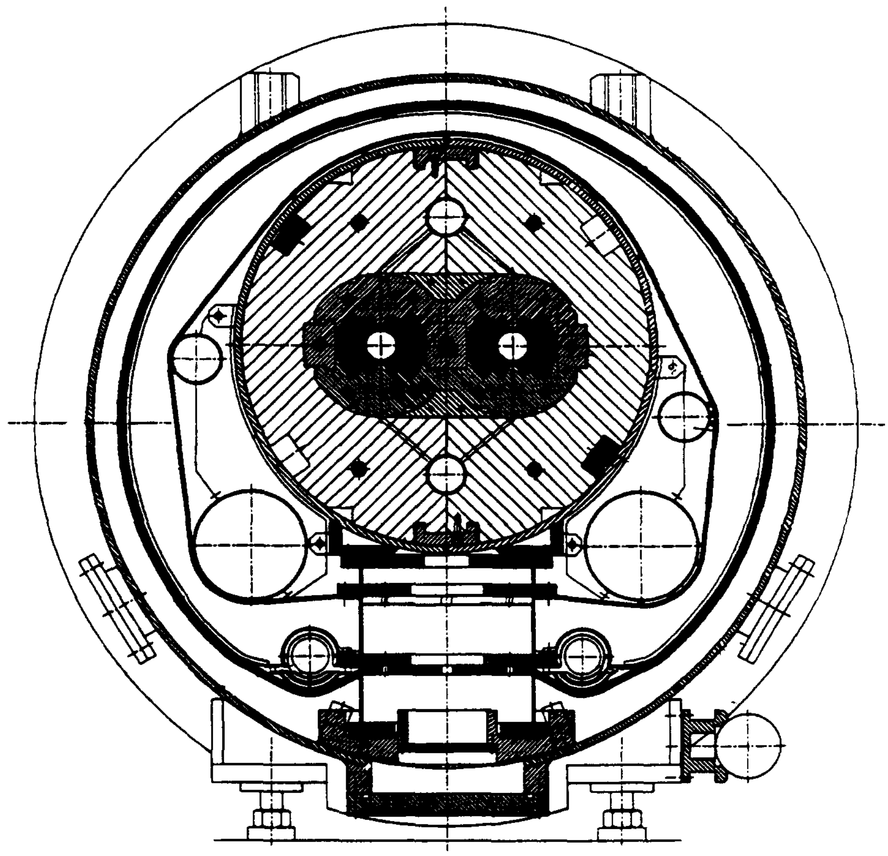


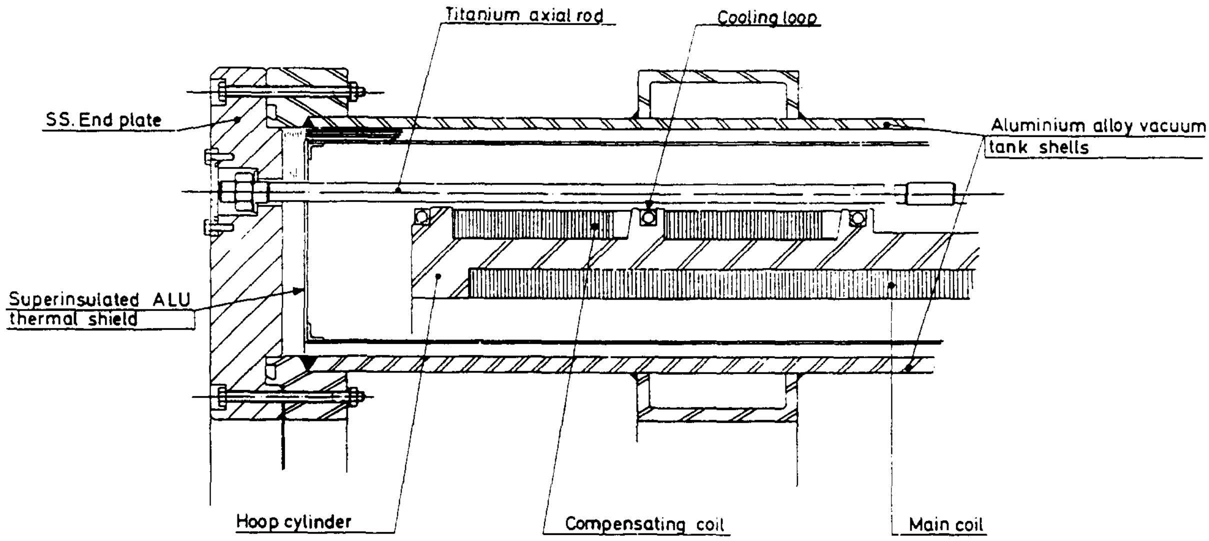
Fig. 8 Double aperture dipoles of the LHC

7. LARGE SOLENOIDS FOR PHYSICS DETECTORS

Most of the electro-magnets for collider-type experiments tend to be equipped with superconducting, solenoid coils with flux densities in the range 0.5 to 1.5 T. Up to now, the maximum dimensions allowable have been limited by the possibilities of transport by road; it may well happen that in future much larger solenoids will be required, in which case they will have to be wound on site.

As an example of a recent design, the solenoid of the Aleph experiment at LEP, which has already operated very successfully for over two years, will be described [18]. The aim was to provide a highly uniform magnetic field of 1.5 T in a cylindrical region of about 3.6 m diameter (where the most critical tracking detector, the TPC or Time Projection Chamber, was to be located), while also housing the sleeve-shaped electro-magnetic calorimeter. As a result, the inner diameter of the cryostat is 4.96 m and its length is 7.0 m.

An outer yoke of iron plates carries the return flux and is also used as the absorber for the hadronic calorimeter. The current conductor (1 712 turns in a single layer with 5 000 A nominal current) is made of an NbTi cable embedded in a rectangular aluminium strip, and is wound on the inside of a support cylinder. The cooling is done by liquid helium at 4.4 K flowing inside a set of pipes attached to the outer surface of the coil cylinder (Fig. 9).



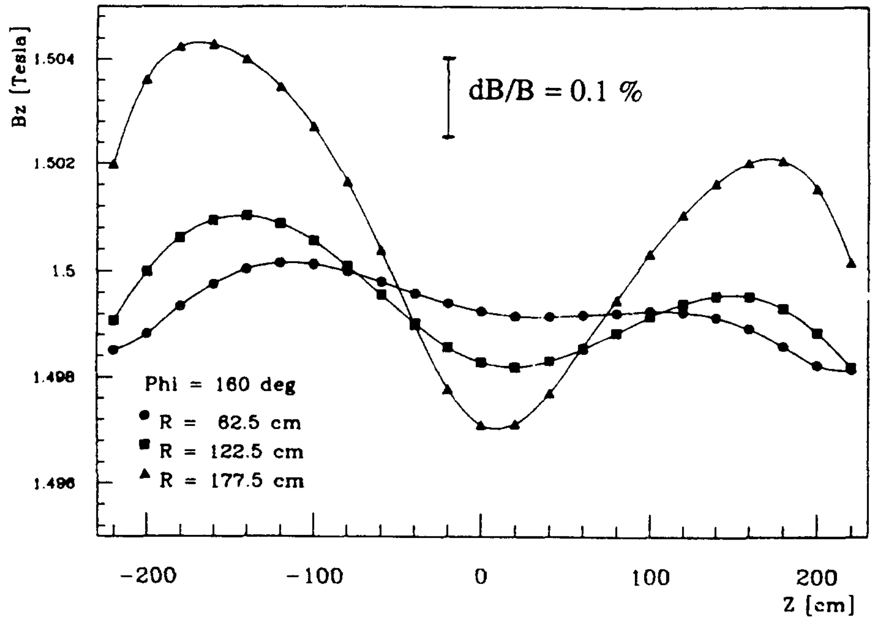
Cross-section through the end of the solenoid

Fig. 9 Construction detail of the Aleph solenoid

Because of the high value of the stored energy (136 MJ), the ramping up and down of the current must be done slowly (in 1.5 h). A fast resistive discharge system (time constant 100 s) protects the coil in case of serious disturbances.

The field uniformity can be optimized by energizing appropriately the compensating windings located at each end. The desired characteristics have been obtained (Fig. 10), e.g. the axial component of the field, B_z is constant to within 2 10^{-3} at the largest radius of interest. The uniformity of the magnetic field, together with the quality of the electric field required for the longitudinal drift of the ionization electrons produced along the particle track to be measured, results in an excellent geometrical resolution of the TPC (as small as 160 μm for radial tracks, in the transversal plane).

It is interesting to note that, while several precise techniques exist to map a magnetic field in space, this is not so for an electric field, which is much more liable to be perturbed by the measuring device or by electrostatic charge accumulation. Therefore, in the case of the Aleph TPC, the uniformity of the electric field was deduced from the residual distortions of the projected tracks and from the known map of the magnetic field.... In a certain sense, therefore, magnetism has taken its revenge after many centuries of neglect!



Main field component: B_z versus z at three radii and fixed azimuth

Fig. 10 Magnetic field uniformity of the Aleph solenoid

8. MAGNET ALIGNMENT

The components of an accelerator and of its experimental equipment must be aligned carefully. For the magnets in particular it is important that the magnetic field regions be located in a precise geometrical relation with the particle orbits. The accuracy required varies with the type of magnet and with its position in the structure. For instance, transverse displacements of quadrupoles are very harmful because they are equivalent to the addition of an unwanted deflecting field on the central orbit. The alignment of pure dipoles, on the other hand, is not critical in this respect, while a transversal tilt introduces a horizontal field component; a transversal tilt of quadrupoles introduces coupling between the two orthogonal oscillation planes (which one tries to keep independent), and so on.

The longitudinal position of the accelerator elements in a circular machine has also a direct influence on the orbit length. This is important whenever considerations of particle synchronization and revolution frequency play a rôle.

The alignment problem has at least two aspects, mainly the position errors of each element with respect to an ideal geometrical figure, and the relative alignment of the elements in a limited, local domain. This latter, "smoothing" requirement is often the most important and must be carefully controlled during the life of a machine. In addition, it is readily affected by local deformations and inequalities of the foundations.

The specialized metrology of large scientific equipment has become an art in itself, and the present school has a session dedicated to it. We should like to quote some of the results reached recently on the 27 km long LEP machine at CERN [19], which with its more than 4 500 functional elements to be aligned, required about 32 000 measurements. First of all, large accelerators tend to be located deep underground and the work of the metrologist must start well before the tunnel is excavated. A geodetic reference grid, based on survey measurements, was built to start with, with r.m.s. errors of 1.5 mm.

This preliminary phase of the work includes measurements of the local anomalies of the gravity vector (due, for instance, to mountain ranges) with respect to the reference ellipsoid. Note also that beyond about one hundred metres the curvature of the earth comes into play. Thereafter the surface reference points are lowered to the machine level (which may be 150 m below ground) at the bottom of the shafts. The tunnelling work then has to be guided, in the absence (it should be noted) of any other reference for as long as the tunnel arcs are not joined together.

For LEP the closure for the civil engineering work has been achieved with a r.m.s. error of as little as 10 mm (1 σ).

In order to be placed correctly along the machine circumference, each magnet element must be equipped with reference marks, which in turn must be located precisely with respect to the magnetic symmetry axes. This is part of the magnetic measurement campaign, in itself an essential phase of the work, which usually assures an accuracy of 0.1 mm r.m.s.

The alignment of the machine components was made with instruments capable of a precision and/or resolution of 0.01 mm in distance and 0.01 mrad in tilt angles.

The most sensitive elements (the quadrupoles), after a first alignment, were "smoothed" to give an r.m.s transversal error of 0.1 mm relative to their neighbours.

Dipoles and other elements were then aligned with respect to the quadrupoles, to give transversal r.m.s. errors of 0.3 mm; tilt measurements and settings were made to within 0.1 mrad r.m.s. Concerning the verification of the theoretical length of the machine circumference (reference orbit) a comparison between the measurement derived from the revolution frequency (precise to 2 mm r.m.s.) and the result of the metrology work, indicated a discrepancy of only 10 mm (i.e. about 0.4 mm/km).

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