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USE OF PERMANENT MAGNETS IN ACCELERATOR TECHNOLOGY:
PRESENT AND FUTURE

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USE OF PERMANENT MAGNETS IN ACCELERATOR TECHNOLOGY:
PRESENT AND FUTURE*

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ABSTRACT

Permanent magnet systems have some generic properties that, under some circumstances, make them not only mildly preferable over electromagnets, but make it possible to do things that can not be done with any other technology. After a general discussion of these generic advantages, some specific permanent magnet systems will be described. Special emphasis will be placed on systems that have now, or are likely to have in the future, a significant impact on how some materials research is conducted.

FOREWORD

Due to a large number of previous commitments, it is impossible for me to find the time to write a paper before the deadline that describes in the standard fashion the content of the talk that I gave at the conference. While Dr. Sankar, one of the chairmen of this symposium, accepted this as a matter of fact, he nevertheless wanted me to contribute something to the proceedings. As a consequence, I proposed to write a paper in a very unconventional manner that reduces the work involved significantly: After an introduction, I will simply reproduce (most of) the viewgraphs I showed in my talk, and give a detailed legend for each figure, but without connecting text, hoping that this will trigger the memory of the audience present at the symposium sufficiently to be useful. Dr. Sankar graciously agreed to this proposal. Since this is an experiment of sorts, I would greatly appreciate blunt comments, both positive and negative, from all readers willing to contribute to this experiment.

INTRODUCTION

Even though it may seem that the purpose of this paper is the description of some very specific devices, that is not the intent. It is the purpose of this paper to first explain some generic properties and advantages of a class of permanent magnet materials, and then to explain a number of very general design concepts that happen to be applied to components that are used in accelerators. I will first describe general purpose components (bend magnets, lenses) that are essential for the operation of an accelerator or storage ring, illustrated with specific examples. I will then follow that up with an explanation of the functioning, and specific examples, of special devices (undulators/wigglers) that allow accelerator technology to serve other disciplines, among them materials research.

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ADVANTAGES OF PM SYSTEMS

- Strongest fields when small
 - Compact
 - Immersible in other fields
 - "Analytical" material
 - No power supplies
 - No cooling
 - No power bill
- }
 }
 }
 }
 }
 }
 }
- Reliability
 - Convenience

Fig. 1 Of the many advantages of PM systems, the one listed on top of this figure is the one that is usually the most exciting. The reason for the advantage listed on top is the following: When one scales an electromagnet in all dimensions while keeping the magnetic field at equivalent locations fixed, it is easy to see that the current density in the coils scales inversely proportional to the linear dimensions L of the magnet. Since superconductors have an upper limit for

the current density j that can be carried, and dissipative coils have an upper limit for j due to the need to remove the dissipated power, j needs to be reduced below that prescribed by simple scaling when L reaches a certain small value that depends, of course, on many details of the magnet design. When j is reduced, the field in a magnet that does not use iron obviously is also reduced, even if the total Ampere turns are maintained by increasing the coil size. The same is also true for a magnet using iron, since an increase of the coil size invariably leads to a field reduction due to increased saturation of the iron. PM, on the other hand, can be scaled to any size without any loss in field strength. From this follows that when it is necessary that a magnetically significant dimension of a magnet is very small, a permanent magnet will always produce higher fields than an electromagnet. This means that with permanent magnets one can reach regions of parameter space that are not accessible with any other technology. The critical size below which the PM out-performs the electromagnet depends of course on a great many details of both the desired field strength and configuration as well as the properties of the readily available PM materials. In the region of the parameter space that is accessible to both technologies, the choice of one technology over the other will be made on the grounds of cost or convenience, (main specifics: power supplies, power needed to run the system, equipment associated with cooling) and in this arena permanent magnet systems are often also preferable, but less so the larger the smallest magnetically relevant dimension becomes.

The other advantages listed are self-explanatory, except for the meaning of "analytical" material. What I mean by that is the fact that the magnetic properties of charge (current) sheet equivalent materials (see Fig. 4) are so simple that they can be described by very simple analytical expressions.

Fig. 2 After a powder, with grains equal in size to ferromagnetic domains, has been oriented in a magnetic field, sintered, and cooled to room temperature, it is exposed to a strong magnetic field parallel to the crystalline axis of the grains. Fig. 2 shows the resulting magnetization curve. It is assumed throughout, that the material is never driven beyond the knee of that curve.

Fig. 3 Shows the resulting $B(H)$ curve both in the direction parallel and perpendicular to the preferred direction, commonly called the easy axis. The remanent field for rare earth materials varies between .8 and 1.2 T, and for various ferrites between .3 and .35 T. The differential permeabilities are as small as 1.03 for some materials, and rarely larger than 1.15.

$$B_n = \mu_0 \mu_n H_n + B_r \quad \left\{ \begin{array}{l} \vec{B} = \mu_0 \hat{\mu} \times \vec{H} + \vec{B}_r \\ B_t = \mu_0 \mu_t H_t \end{array} \right. \quad \vec{H} = \vec{J} \times \vec{B} - \vec{H}_c$$

this $\rightarrow$ into $\text{curl } \vec{H} = 0$ or $\text{div } \vec{B} = 0$.

$$\text{curl}(\vec{J} \times \vec{B}) = \text{curl} \vec{H}_c = \vec{J}_{eq}, \text{ or } \text{div}(\mu_0 \hat{\mu} \times \vec{H}) = -\text{div} \vec{B}_r = \vec{J}_{eq}$$

This represents passive material ($\vec{J}_I, \hat{\mu}$)
with active terms/properties ($\vec{J}_{eq}, \vec{B}_r$)

Homogeneous magnetization

$\vec{J}_{eq} \rightarrow$ current sheet $\rightarrow$ CSEM
 $\vec{B}_r \rightarrow$ charge sheet $\rightarrow$

Fig. 4 Shows that magnet properties can be described, in addition to "frozen magnetization" (Fig. 2) and $B(H)$ curve (Fig. 3), by an anisotropic permeability very close to 1, plus either an impressed current or charge distribution, which, for the usual case of homogeneously magnetized material, corresponds to current or charge sheets on the surface.

Fig. 5 Demonstrates the easy axis rotation theorem (Ref.1), which says: in an iron-free, two dimensional system, rotation of the easy axis of all CSEM of the system by any given angle keeps the magnetic field strength everywhere outside the material fixed, but rotates the field direction by the same angle in the direction opposite to the rotation direction of the easy axis. This theorem gives a lot of insight that can be used to great advantage in the design of systems.

Fig. 6a To keep beams together, focusing is necessary.

b $E = v \times B \rightarrow$ Magnets if $v/c > .03$
2D

6b Magnets give more focusing than electric fields that are limited by breakdown when $v/c > .03$.

c $V(r, \varphi) = \text{const.} \cdot r^n \cdot \cos(n\varphi) \rightarrow B \sim r^{n-1}$

6c 2D scalar potential for useful field distributions.

- d
{	1	Use of magnet	
	2	bend magn	dipole
	3	lin. focus. (AG)	quadrupole
	4	{ correction of aberrations	

6d Classification of magnet types.

Fig. 7 A doublet assembled from lenses of equal focusing and defocusing strengths can always be made focusing in both directions.

$$\alpha(r, \varphi) = \arctan \frac{y}{x}$$

Fig. 8 Using "frozen magnetization," and with it the linear superposition principle, the question "what is the optimum orientation of the easy axis of material anywhere to produce a given field distribution?" is a good question that has a very simple answer in the case of 2D iron-free multipoles (Ref.1).

Fig. 9 Material with continuously changing easy axis orientation is very difficult to make. Therefore one uses segmented multipoles, (Fig. 9 shows a quadrupole.) Material in each block is homogeneously oriented and magnetized in the ideal direction for the centerline of block.

2 D QUADRUPOLE FIELD

$$B_x - i B_y = B_r \frac{x + iy}{r_1} \cdot 2 \cdot \left(1 - \frac{r_1}{r_2}\right) \cdot \frac{\sin(2\pi/M)}{2\pi/M} \cdot \cos^k(\pi/r_1)$$

Possible Harmonics: $n = 2 + 1/M$; $M = 0, (1), 2, \dots$

2 D Dipole

$$B_x = B_r \cdot \cos(\pi/r_1) \cdot \frac{\sin(2\pi/M)}{2\pi/M}$$

Fig. 10 Gives the field for a 2D iron-free segmented quadrupole and dipole. M is the number of blocks in the magnet, and r_1 and r_2 are the inside and outside radii of the magnet (Ref. 1). Both magnets can produce fields larger than B_r . When M is reasonably large, the loss of field strength due to segmentation is very small.

Fig. 11 Segmented dipole. This type of magnet can also be used to provide the main field for magnetic resonance imaging.

Fig.12a,b These are two sextupoles that can be used for electron cyclotron resonance ion sources. The easy axis rotation theorem tells us that both configurations have essentially the same fields. Configuration b is preferable because some plasma will escape along radial field lines, leading in case b to heating of the vacuum chamber between permanent magnet blocks, and not right under them as is the case with configuration a.

Fig. 13 Shows schematically a PM quadrupole with adjustable field strength. In this hybrid magnet, the dotted material is soft iron. The field distribution is controlled by the iron surface, thus it is very insensitive to material properties as long as the permeability of the iron is large compared to 1. The arrows indicate the easy axis of the CSEM. By rotating the outer ring with the attached CSEM one can clearly change the field

strength in the central region. I design such systems with a design code that consists of an appropriately linked set of analytical formulas. This is possible only because the material is "analytical."

Fig. 14 Shows an arrangement of soft iron and CSEM to serve as a multiple beam focusing system.

Fig. 15 Shows schematically a hybrid dipole. By drilling a hole through the whole magnet along the vertical center line, one can produce a strong magnet that can, under some circumstances, replace a solenoid. However, for this kind of solenoidal field magnet, the line integral of H along the whole vertical centerline is, because of Ampere's Law, always identically zero.

Fig. 16 Shows a solenoidal field doublet.

c) $\theta_w / (1/\delta) = \theta_w \delta = K = \frac{B_0 / k_u}{m_0 c / e} = .934 B_0 (T) \lambda_u (cm)$

f) $\lambda_r = \frac{\lambda_u}{2\gamma^2} \left(1 + \frac{K^2}{2}\right)$

Fig. 17 is a very brief synchrotron radiation tutorial. 17a Shows schematically the radiation emitted by an electron circulating in a homogeneous field which is equivalent to the field in the bend magnet of a synchrotron or an electron storage ring. At any instant, the radiation is emitted essentially in a cone of opening angle $2/\gamma$ centered along the forward direction of the motion of the electron. γ = energy of the electron divided by its rest energy, = 2000 for an energy of 1 GeV.

17b By providing a field that periodically changes direction, one can get much more radiation, and one can change the field strength in this kind of magnet called an undulator (U) or wiggler (W) without affecting the operation of the storage ring, thus allowing one to change the properties of the radiation.

17c The ratio of the angle between the extreme trajectory directions and the natural radiation cone angle is called the deflection parameter K .

17d To understand synchrotron radiation better, it is useful to describe the physics phenomena first in a coordinate system that moves with a constant velocity that equals the average velocity of the electron in the U or W. Assuming first a very small magnetic field, the electron experiences a weak electric field, leading to a linear motion, which in turn causes radiation to be emitted in the manner shown. Observed from the laboratory frame, one expects to see the pattern shown on the right.

17e When the field becomes sufficiently large, the electron will not move linearly any more, but executes a figure 8-like motion, leading to harmonics which, when K is sufficiently large ($K > 3$), leads to so many overlapping harmonics that one is dealing with an essentially continuous spectral distribution. In this case, the magnet is called a wiggler.

17f When K is much smaller than 1, (as described in Fig. 17d), only the fundamental is excited, and it is quantitatively given by Fig. 17f. λ_u is the undulator period length, and θ is, in this case, not the extreme trajectory angle, but the direction of observation.

- *Element sensitive biology*
- *Interface, thin films, and material sciences*
- *Chemical kinetics and photochemistry*
- *Atomic and molecular science*
- *X-ray Lithography*

Fig. 18 This is a partial list of applications of synchrotron radiation. Even though U and W are used now in synchrotron light sources, the storage rings were not specifically designed to take advantage of the light that can be produced with U and W. A new generation of synchrotron light sources is being designed (with construction to start very soon) that will take advantage of the properties of modern permanent magnet U and W.

Trace Element Profiles Along a Sample Are Measured in Air with Part-per-Billion and Femtoqram Sensitivities

LBL Hard X-ray Microprobe
SSRL, BL 6
10 keV photons

Fig. 19 Shows one example of the application of synchrotron radiation: a series of element sensitive scans of an alga filament.

X-ray Microprobe With Multilayer Mirrors for Materials and Biological Studies

Fig. 20 Shows an experimental setup typical for the kind of research described in Fig. 19.

Fig. 21 Shows an iron-free U/W. The performance is obtained by taking the performances of a multipole, and letting the radius go to infinity while keeping the distance between poles fixed, thus leading to one linear array. The complete U/W consists of 2 such arrays and its performance is given in Ref. 2. The easy axis rotation theorem again tells us that blocks with

their easy axis parallel to the symmetry plane contributes as much to the total field as the other blocks do.

Hybrid Insertion Device configuration with field tuning capability.

Fig. 22 Shows schem- atically the crosssection of an U/W that uses both soft iron and CSEM. Again, this magnet is not nearly as sensitive to material properties as the iron-free U/W.

PURE CSEM AND HYBRID
UNDULATOR/WIGGLER PERFORMANCE
FOR NdFe ($B_r = 1.1$ TESLAS)

Fig. 23 Gives the achievable fields for the two types of U/W described so far.

Fig. 24 In some types of free electron lasers (i.e. synchrotron radiation produced by large arrays of "fat" electrons, i.e., bunched with light wave periodicity) a substantial fraction of the energy of the electrons is converted into light, requiring an adjustment of the resonance condition (see Fig. 17f) due to the changing value of γ . One way to do that is adjustment of K through B . Since one needs

to have a reasonable adjustment range for B , one would like to use an electromagnet (em). This requires a quantitative understanding of the field limitation in an em U/W. From this Figure, showing a periodic em, it is clear that one needs to analyze only $1/4$ of a period in one half of the magnet.

Fig. 25
Shows 1/4 of a period. Taking the line integral over H along the path going from the lower left corner up into the iron along the left problem boundary to a point higher than the coil, to the right boundary, down the right problem boundary, to the bottom boundary, and then left to the starting point, one obtains the upper of the two equations. Ignoring the saturation term

(if it's significant, the design is not useful), one obtains the expression shown for the height D_2 of the coil. For a given desired field H and a maximum "coolable" current density j , one obtains a D_2 that is independent of the absolute size of the device. Since the flux going into the top of the pole is proportional to both H and D_2 , the iron at the top will saturate very strongly if the width of the pole at the top (scaling with the period length) becomes too small.

Plan view of iron poles of U/W

Fig. 26 In reality, saturation will be worse because of the lateral width of the pole, as is clear from this figure, showing a plan view of the U/W (with the beam going from left to right), with fieldlines also shown schematically. This figure also suggests a solution: attach CSEM to the poles, with the easy axis oriented in such a way as to put flux into the pole in the direction opposite to the

Plan view of PM assisted em V/W

Fig. 27 Shows schematically the complete arrangement.

Fig. 28 Since the CSEM pre-loads the pole with flux (i.e. with the power supply off, there is flux going through the pole because of the CSEM) one expects an asymmetric saturation curve that allows one to reach a higher peak field than is possible without CSEM, and this saturation curve, taken from a log book, shows asymmetry as expected.

Fig. 29 Shows schematically an U/W when the concepts outlined above are carried to an extreme, leading to very high field levels.

Fig. 30 Shows a similar way to use CSEM in an em, in this case a quadrupole. Shown is 1/8 of the complete magnet, with CSEM close to the aperture region.

Fig. 31 Shows a field line pattern in the magnet depicted in Fig. 30. It is clearly visible how the CSEM reduces the flux density in the pole, making it possible to produce higher fields in the aperture, to reduce the size of the magnet, and making it less sensitive to iron properties.

LB
Variably Polarized Radiation Can Be Generated with Crossed Undulators In Low Emittance Storage Rings

Fig. 32 For some applications it is desirable to produce circularly polarized synchrotron radiation, and the system shown here is a very clever and elegant way to do that; see Ref.3. Looking at the light emitted by one electron at a location just in front of the monochromator, one will find two wave trains with orthogonal linear polarization, separated in time, and each wave train containing the same number of

optical periods as the number of periods in each undulator. A monochromator of sufficient resolution will increase the number of periods in each wave train, making them overlap and thus produce circularly polarized light, if the delay between the wave trains has been adjusted properly. By adjusting that delay in the way indicated, circularly polarized light of either helicity can be produced.

Fig. 33 Another method to produce circularly polarized light is to produce synchrotron radiation in a helical magnetic field. A conceptually simple way to produce such fields is to use short segmented dipoles of the kind described in Fig. 11, with each dipole rotated by a given angle relative to its next upstream neighbor (Ref. 2). A still different method is to use the basic hybrid U design, but excite the

poles not with the standard symmetry pattern shown in Fig. 33a, but the antisymmetric pattern shown in Fig 33b. If, in addition, one arranges the poles not perpendicular to the center electron trajectory but at an angle as shown in Fig. 33c, such a magnet has helical fields of opposite helicity above and below the midplane (Ref. 4) that could be used by stored electron beams since they are always very small in the vertical direction.

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