Magnet Innovations for Linacs

Klaus Halbach

Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720

Abstract

It is possible to produce large magnetic fields at the aperture of permanent magnet quadrupoles, even when the magnetic aperture is very small. That, combined with their compactness, makes permanent magnet quadupoles very powerful components of small aperture linacs. Results will be presented about past and present work on both fixed and variable strength permanent magnets suitable for use in and around linacs.

1) Introduction

While the acceptance of permanent magnet (PM) insertion devices for the generation of light with synchrotron light sources and free electron lasers was very fast and widespread after their initial introduction[1,2], acceptance of PM multipole magnets seems to take some what longer, even though the iron free PM multipoles were described earlier [3,4]. I will therefore describe again briefly both the generic advantages of permanent magnet systems as well as the specific advantages and limitations of individual magnets that have been described before. In addition, some concepts will be presented that have not been described in print before.

2) Generic Advantages of Permanent Magnet Systems.

Fig. 1 lists the main generic advantages of PM systems. Of these advantages, I consider the first listed advantage the most important one, and I will therefore comment on it in some detail: If one scales all linear dimensions of an electromagnet and wants to keep the field strength fixed everywhere, the current density in the coil has to scale inversely proportional to the linear dimensions, leading to insurmountable cooling problems when the linear dimensions become smaller than a value that is specific for each geometry.

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

Fig. 1 Advantages of PM Systems

If one is forced to reduce the current density in an iron free magnet, the field strength will go down as a consequence. In an electromagnet that uses iron in addition to coils, reduction of the current density can be made up by increasing the coil size. However, that leads invariably to increased saturation of the iron. It is this combination of limitations of the current density of the coil and the saturation induction of the iron that leads to a reduction of the fields that can be produced in such a magnet when the linear dimensions need to be small. Since the fields produced by a PM do not change when one scales all dimensions, PM will always outperform electromagnets when the linear dimensions are small enough. The size where this occurs is very different for different geometries. While the critical period length for a wiggler or undulator is of the order 30cm, the critical aperture for a quadrupole is of the order 1 cm. These numbers hold for anisotropic permanent magnet materials (PMM) like Samarium-Cobalt or Neodymium-Iron-Boron with a remanent field Br of the order .9-1.1 T and a coercive field $\mu_0 H_c \geq .9\cdot Br$, and the use of such a material is assumed throughout this paper. As will be shown in sect. 5, switching to an "all permanent magnet" system is not the only answer: By using PMM judiciously in an electromagnet, its performance can be upgraded to that of a PM system.

3) Iron Free PM Multipoles

Even though iron free PM sextupoles are used [5] because of the combination of compactness and field strength, quadrupoles are discussed in more detail because it is the most frequently used member of this family of magnets. Fig. 2 shows a schematic cross section of a segmented quadrupole. The field at the aperture is given by

$$B = 2\eta Br\,(1-r_1/r_2). \qquad (1)$$

r_1 and r_2 are inside and on outside radius of the magnet, and η depends on the segmentation and equals .94 for the magnet shown in Fig. 2 (A complete and general set of formulas for all multipoles is given in ref. 4. The advantages of this type of magnet is the obtainable strength, combined with rather small size, making them especially suitable as focusing elements in drift tube linacs [6]. Even though some work has been done to develop quadrupoles of this type that have adjustable strength [7], implementation of these schemes is not easy. Therefore, this type of quadrupole has been used only in the fixed strength configuration.

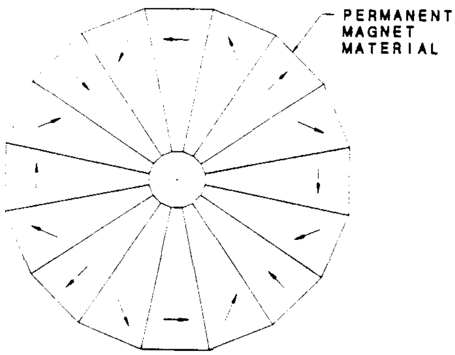

Fig. 2 Iron Free PM Quadrupole

While the harmonic content of this type of multipole is very good in principle [4], material imperfections produce virtually all harmonics. These field errors can be fairly easily corrected if one designs the magnet in such a way that the individual blocks can be moved accurately and reproducibly by small distances after original assembly. The movements necessary to correct a measured set of harmonics can easily be calculated with the information given in ref. 8. For the magnet not to change magnetic properties with time, it is imperative to cycle its temperature at least once to a value higher than the highest anticipated temperature during its life.

Since funneling will be discussed at this conference, it is appropriate to mention a somewhat unusual utilization of iron free dipoles and quadrupoles. Fig. 3 shows a cross section of an eight piece segmented dipole. The field produced by such a dipole is given by
$B = .9 \cdot Br \cdot \ln r_2/r_1$, or for $r_2 - r_1 \ll r$,

$$B = 1.8\ Br \cdot (r_2 - r_1)/2r_1, \qquad (2)$$

and it can obviously be used as a septum magnet.

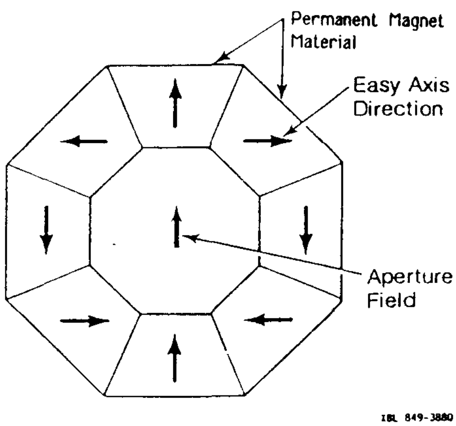

Fig. 3 Iron Free PM Dipole

The performance limitation of this septum magnet is quite different than the performance limitation of conventional septa: The achievable field depends on the needed septum thickness ($r_2 - r_1$) divided be the beam size ($2r_1$), not on absolute dimensions. In order to eliminate weak stray fields outside the dipole, one needs to attach a thin iron sheet to the outside of this dipole. While hardware has not been built, computer studies show that this septum magnet should perform extremely well.

One can consider variations on this theme: One could, for instance, use to the right of the ring shown in Fig. 3 another ring. Producing with that ring a field of opposite polarity, and placing its left most block on top of the right most block of the ring shown in Fig. 3 leads, essentially, to a cancellation of the effects of these two blocks, so that one can leave them out altogether. This magnet has no septum at all, but a field region where the fields are badly distorted. The difference of the fields adjacent to this "immaterial" septum is twice the value given by equation 2. Another way to gain a factor 2 over equation 2 would be to use a segmented quadrupole, provided focusing in the bend plane is permitted.

4) Adjustable Strength Hybrid Multipole

In order to regain the strength adjustability the electromagnetic multipole provides, the adjustable strength PM multipole was developed. I discuss again, as the representative member of this family, the hybrid quadrupole. It uses both PM and iron in the configuration shown in Fig. 4. The

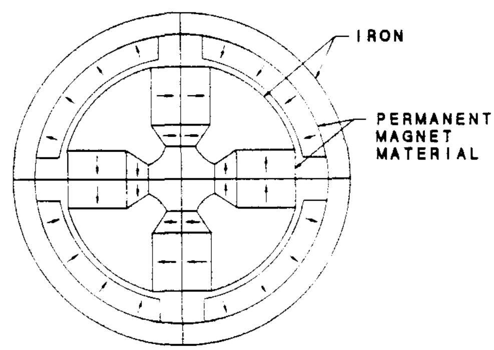

Fig. 4 Hybrid Quadrupole

gradient can be adjusted by rotating the outer iron ring with the attached PMM, making this quadrupole suitable for use in drift tube linacs that have to accelerate particles with different mass to charge ratios. Some prototype quadrupoles have been built [10]. They performed as expected, and a quadrupole is being built at LBL that will be used for life time testing by cycling the gradient 100,000 lines (we hope) up and down. To characterize this type of magnet, the following comments are in order.

A) Because iron is used in this magnet, one cannot obtain quite the high gradients that are possible with iron free PM quadrupoles. By using Vanadium Permendur, aperture fields of 1.2-1.4T can be obtained, a significantly higher value than achievable with a small aperture electromagnetic quadrupole. Also, while not quite as compact as the iron free PM quadrupole it beats the electromagnet in this respect also.

B) The field distribution is controlled by the iron contour, and the value of the scalar potential on the iron surface shaping the field. One can assure that these potentials have the proper values by measuring carefully the PM blocks, and placing them accordingly. If possible, proper scalar potentials can be guaranteed absolutely by connecting the members of each pair of poles that has to be on the same potential by soft iron "scalar potential buses" at the end(s) of the magnet. The shaping of the pole contour is done essentially with the same procedures that are used to design the pole contour of electromagnet quadrupoles.

C) This magnet is a good example of the practical importance of the simple way with which the magnetic properties of Rare Earth PM can be described: To design a magnet as shown in Fig. 4 properly, one has to choose correctly a large number of parameters. Although this is a matter of style, I do not see how one can come up with a good design in an acceptable time span without a set of essentially analytical design formulas, using a "number cruncher" only at the % accuracy level. Important is, of course, not only that set of formulas, but the understanding these formulas both imply and generate.

5) Laced Quadrupole

Under some circumstances, the mechanical complexity and/or lack of speed associated with the field strength adjustment method inherent in the design described in sect. 4 may be undesirable. For that reason, an electromagnet that does not suffer the field strength reduction associated with small dimensions would be a desirable device. While undulators and wigglers with these properties have been developed [11], the underlying concepts were somewhat limited and application and device specific. The method of use of PMM in an electromagnet described here is, in contrast, applicable to <u>any</u> electromagnet. To explain the concept, I use again the quadrupole as the most important member of the multipole family.

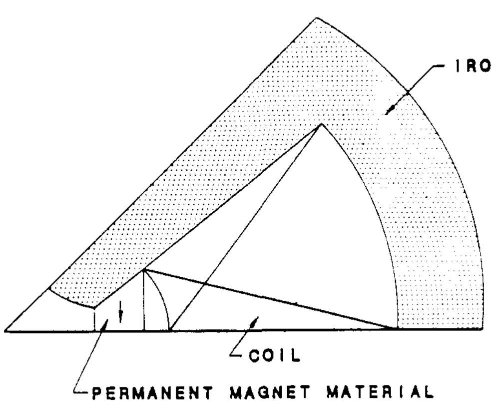

Fig. 5 45° Section of Laced Electromagnetic Quadrupole

Fig. 5 shows schematically a 45° slice of the cross section of a quadrupole that uses both a coil and PM. In a conventional small aperture electromagnetic quadrupole, a lot of flux enters the pole in the region just beyond the shaped pole contour. For fixed current density in the coils and fixed field at the magnet aperture, the resulting saturation of the iron increases as the aperture decreases. By placing PMM into this region, as shown in Fig.5 and in the field line pattern plot in Fig. 6, this flux is dramatically reduced, making it possible to reach the same aperture fields quoted for the hybrid quadrupole.

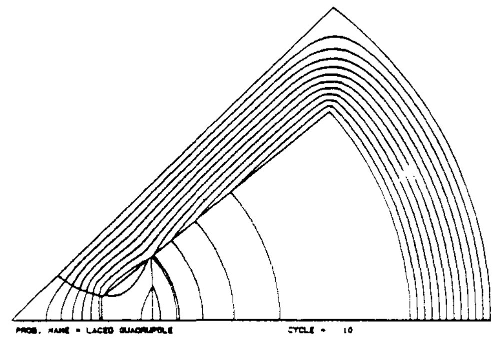

Fig. 6 Magnetic Field Pattern in 45° Section of Laced Electromagnetic Quadrupole

This basic concept can, of course, be modified in many beneficial ways: one can tilt the PMM block, one can use a direction of the easy axis that is not parallel to the edge of the block, one can put PMM even closer to the aperture than shown in Fig. 5, one can put PM at the ends of the quadrupole, etc. In extreme cases (usually not in quadrupoles, but definitely in magnets like undulators/wigglers) it is even necessary to have alternatingly several blocks of PMM and coils, hence the name laced electromagnet.

That this type of magnet behaves like an electromagnet is clear if one takes $\int H \cdot ds$ along the boundary of the magnet shown in Fig. 5 Application of Ampère's law, and using I for the total Ampère turns in the part of the magnet shown in Fig. 5, yields

$$(\int H r dr)_{ap} = I - (\int \vec{H}\cdot d\vec{s})_{iron} \qquad (3)$$

This equation shows clearly that the presence of the PMM is felt only indirectly: the only term that is affected by the presence of the PMM is the last term, representing the loss of excitation due to saturation of the iron. The indirectness of the effect of the PMM does not mean that the effect is small: The field strength of a hybrid drift tube quadrupole can be improved by a factor 1.5, and the gain can be significantly larger for other structures. Since the iron is preloaded with magnetic flux generated by the PMM, the saturation curve of the magnet is extremely asymmetric, allowing much higher fields in the "forward" direction than in the reverse direction. While this does generally not represent a problem for drift tube quadrupoles, this effect can be quite extreme in other systems. In strong laced undulators, it is not even possible to turn the device off without encountering severe saturation effects.

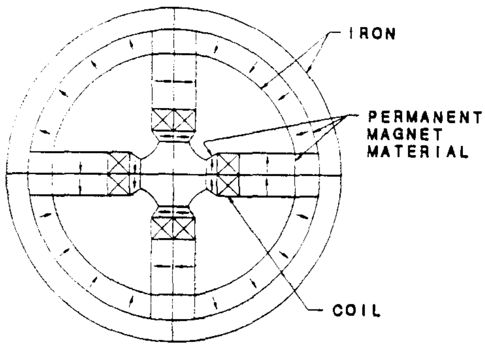

Fig. 7 Laced Electromagnetically Tuned PM Quadrupole

If it is undesirable to have to use a power supply to energize the whole magnet, and if one needs to change the field strength over only a small range, and if mechanical adjustment as described in section 4 is not acceptable, one can use an electromagnetically tuned PM. Figure 7 shows such a configuration, again for the specific case of a quadrupole. In contrast to the magnet shown in Figure 4, the outer iron ring with the attached PMM is not rotated. The field strength change is affected with the coil shown.

6) PM Solenoid Doublett

Solenoidal focusing can be advantageous immediately following an ion source. While PM solenoidal focusing has been developed for electron microscopes [12], the kind of compactness that can be important for our kind of application does not seem to be important for electron microscopes.

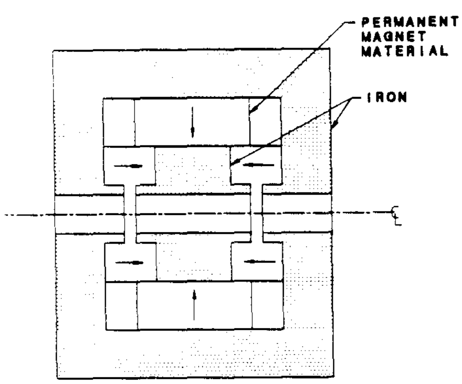

Fig. 8 PM solenoid Doublett

Fig. 8 shows schematically the cross section of a compact PM system that acts like a solenoid doublett. The reason for laying this magnet out as a doublett is the following: Since the integral over H_z on axis must vanish (Ampère's law), one might as well get focusing in the regions of both polarities of H_z. Computer runs show that one can get peak fields of the order 1T as on axis, but hardware has not been built.

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