New Concept for the Design of Highly Effective Magnetic Shields for TOF-MS

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Introduction

Traditional methods of magnetic shielding usually involve completely, or near completely, enclosing a region with high permeability shield material so that the magnetic field within the shield is near zero. This approach is not so readily applied to time-of-flight mass spectrometry situations as there are a number of potential problems with using this type of magnetic shield:

- The shields can create higher magnetic field in the regions surrounding them, adversely affecting the trajectories of ions in the region.
- Such shields can be very large and inconvenient to use.
- They can magnetically couple with any nearby magnetic device and impair the function of that device.

We have developed a new method for analyzing the magnetic fields in shielding structures and determining their impact on ion motion. This analysis has been applied to the design of simple and effective magnetic shield structures for use in TOF-MS applications. This new methodology involves determining the component of the magnetic field that exerts a force on a moving charged particle and then designing magnetic shielding structures that minimize this component of the magnetic field.

This approach often does not involve reducing the magnetic field in which the charged particle is moving to zero (or as close as possible to it), but instead uses structures of magnetically permeable material to locally reorient the magnetic fields so that the force they exert on a moving particle is minimized to a level that is not significant. In some cases Electron-Optical structures that already contain a number of parallel metal elements (plates or rings etc.) can be readily adapted to provide a high level of magnetic shielding either by replacing some of these metal elements with ones manufactured with magnetically permeable metals (i.e. mild steel, mu-metal etc.), or by adding magnetically permeable elements.

Using this method of magnetic shield design it is possible to construct an effective magnetically shielded path for ions that does not have the issue of magnetically coupling with other magnetic circuits or devices that may be in the vicinity (for example a magnetic ion detector).

General Theory

Traditionally, a magnetic shield is designed using high permeability materials (e.g. mu-metal) to reduce the magnetic field strength to a required small level in the region of an ion beam's trajectory.

Figures 1 and 2 show an example of a magnetic circuit and the magnetic equipotential lines surrounding the circuit both in free space (figure 1) and with a nearby tube of magnetically permeable material (figure 2) used to magnetically shield a path for ions to pass by the magnetic circuit.

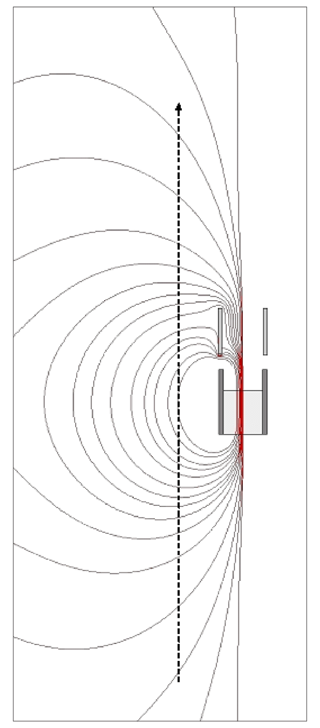

Figure 1. Magnetic equipotentials near a magnetic circuit. The dashed line shows the intended path of ions.

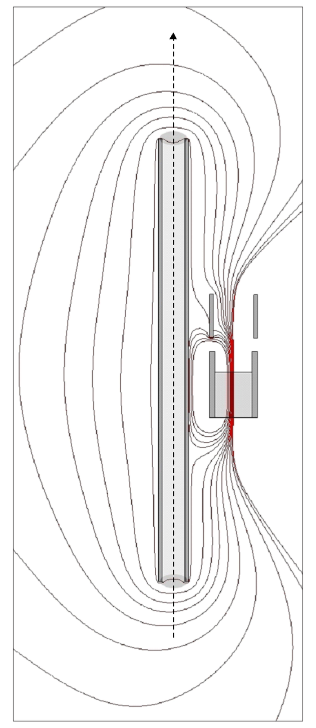

Figure 2. Magnetic equipotential lines near a magnetic circuit with a tube of magnetically permeable material used to create a shielded (field free) path for ions. The dashed line shows the intended path of ions.

There are several problems of a practical nature with using the shielding method of figure 2. A magnetic shield made using a tube of permeable material creates significant distortion to the magnetic field distribution around the shield structure. If such a structure is sufficiently close to a device whose function is sensitive to magnetic fields (e.g. a magnetic ion detector), the distortion in the magnetic field produced by the presence of the shield can impair the function of such a device. This is referred to as magnetic coupling, where the magnetically permeable material of the shield interacts with the magnetic circuit of the device and effectively becomes a part of that magnetic circuit, altering its characteristics.

Another problem with this type of shield occurs when ions enter or exit the shield structure. While having very low magnetic field strength within the structure, there will often be regions of high magnetic field strength at the transitions between the shielded region and the unshielded region surrounding the shield. These regions of high magnetic field strength can influence the motion of the ions if they are required to enter or exit the region enclosed by the shield. The main reason for this is that high permeability materials are in reality not magnetic "shields" (which block magnetic flux from getting into a region), but are in fact magnetic flux conductors that tend to equalize the magnetic potential over its surface. Figure 3 shows a plot of magnetic field strength experienced by an ion as it moves along the ion beam path shown in figure 2. This plots shows regions of higher magnetic field at the ends of the magnetic shield where ions enter or exit the magnetic shield structure.

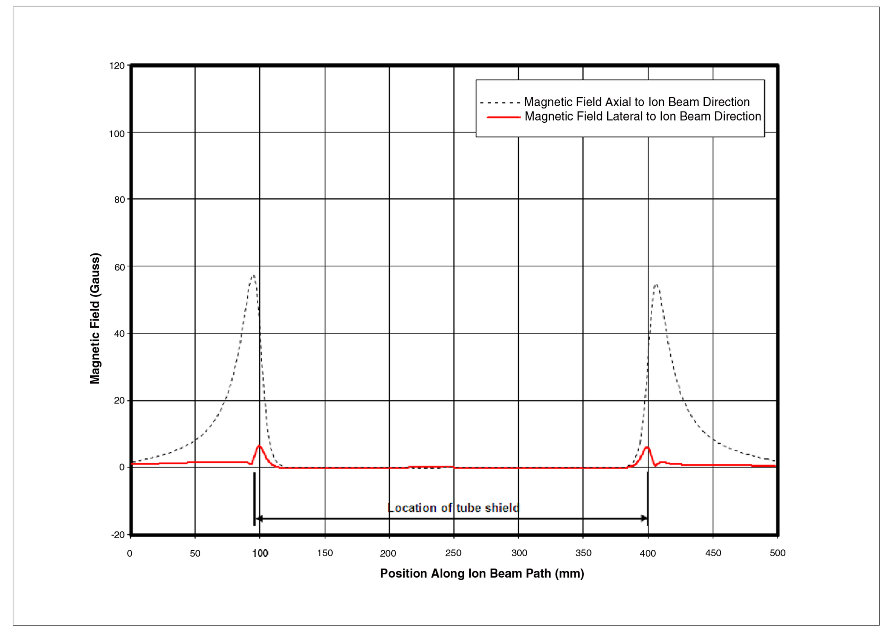

Figure 3. Magnetic field seen along the ion path through a tube of magnetically permeable material. Shown are the axial component of the magnetic field, BA, and the lateral component, BL, is shown in red.

There is another approach to resolving this problem. Instead of endeavoring to reduce the magnetic field to zero in an enclosed region of space, the magnetic field that exists in the region of the ion beam can be modified to exert no force on the ions as they pass through it. In effect, we want to nullify the influence of the magnetic field with respect to the motion of the ions.

The equation for the force on a charged particle moving in a magnetic field is defined by the vector cross product:

$$\underline{\mathbf{F}} = q\underline{\mathbf{v}} \text{ X } \underline{\mathbf{B}} \qquad (1)$$

Where **F** is the vector force exerted on the ion (or other charged particle), **v** is the velocity vector of the moving charged particle, **B** is the magnetic field vector and q is the charge on the particle.

So the magnitude of the force on the particle is given by:

$$\underline{\mathbf{F}} = q \; v \; B \sin\Theta \qquad (2)$$

Where **F** is the magnitude of the resulting force on the charged particle, v is the magnitude of the particle's velocity vector, B is the magnitude of the magnetic field vector and Θ is the angle between the direction of the ion velocity vector **v** and the magnetic field vector **B**.

For the magnitude of the force, F, on the charged particle to equal zero (and the magnetic field to have no effect on the motion of the particle) there are three solutions to equation (2);

1. v = 0, this means the ions are not moving, so this solution is of little interest in mass spectrometry applications where the ions are moving.
2. B = 0, this is the traditional magnetic "shielding" approach.
3. sin(Θ) = 0, (i.e. **v** is parallel to **B**), this means that if the magnetic field in the region of the ion beam is arranged so that it is parallel to the direction of travel of the ions, then the force acting on the moving ions will be zero. In this case, as the magnetic field exerts no force on the ions it is, in effect, nullified.

The third of these possible solutions forms the basis for the design of a new type of magnetic shield.

If we define the axial magnetic field, B_A, as the magnitude of the component of the magnetic field, **B**, which is in the direction of motion of a charged particle, and the lateral magnetic field, B_L, as the magnitude of the component of the magnetic field that is perpendicular to the direction of particle motion. Therefore, at any point along the particle's path, the total magnitude of the magnetic field, B, experienced by a moving charged particle is given by:

$$B = (B_A^2 + B_L^2)^{1/2} \qquad (3)$$

Since B_A is in the same direction as the direction of motion of the charged particle, it exerts no force on the particle and therefore has no influence on the particle's motion. So it is not necessary for a magnetic shield to reduce the B_A component of the field. It is only the value of B_L that influences the motion of moving charged particles, so for a magnetic shield to be effective it is only required that it minimizes B_L.

This approach has been found to be very practical to implement using magnetically permeable materials and can be readily applied to any application involving charged particles with trajectories that could be impacted by the presence of a magnetic field (for example TOF-MS applications).

By using magnetically permeable materials for the purpose of locally re-orienting magnetic fields to be in the same direction as the moving ions, the influence of the magnetic field can be greatly reduced without the need for large shielding structures.

Application to an Ion Beam moving near a Magnetic Circuit

One of the principal problems of traditional magnetic shield structures is that the high permeability material does not really "shield" magnetic fields, but instead creates a surface with uniform magnetic potential. So when such a shield is used to fully enclose a region, the region inside the fully enclosed structure is field free. Also if ions are required to move into, and out of, the shielded region there are typically very high magnetic fields present in the interface between the shielded and unshielded region.

Another problem is that a magnetic shield that distorts the magnetic potential field distribution will also magnetically couple with any nearby magnetic circuit (such as a magnetic ion detector) and this magnetic coupling can impair the operation of the magnetic circuit.

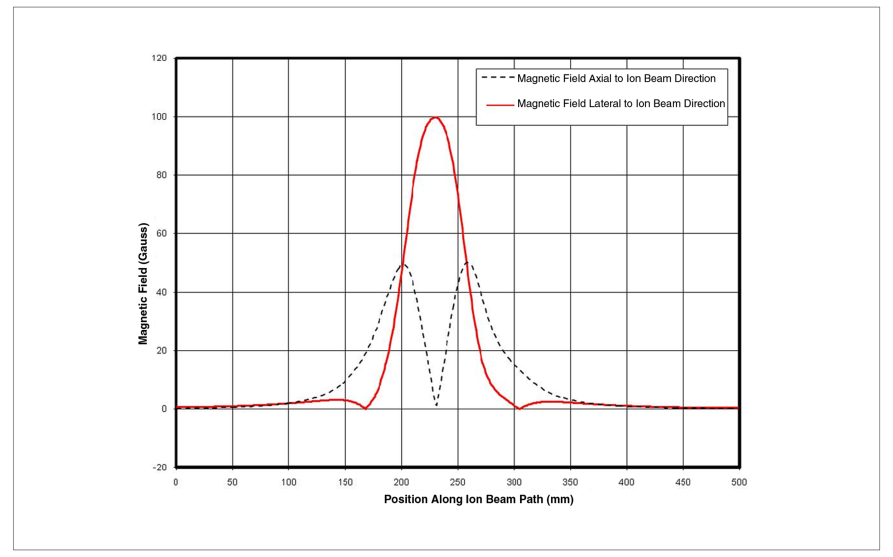

Figure 4. Magnetic field seen along the ion path with no shield in place. Shown are the axial component of the magnetic field, BA, and the lateral component, BL, is shown in red.

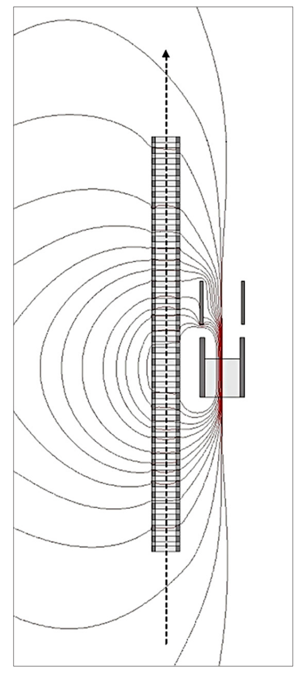

Figure 5. Magnetic Equipotentials near a magnetic circuit. The dashed line shows the intended path of ions. The shield structure shown is a series of alternating rings made from high permeability material (darker) and low permeability material (lighter).

Figure 4 shows the magnetic field experienced by ions moving past a magnetic circuit (such as a magnetic ion detector) as they move along the ion path shown in figure 1 with no shield structure in place. In this example the ions will experience up to 100 Gauss of lateral magnetic field, B_L.

In figure 5 a magnetic shield constructed of alternating high and low permeability material is shown. In this arrangement the magnetic equipotentials are still able to flow through the space occupied by the shield structure, but within the shield structure the equipotentials are now aligned to create a magnetic field that is in the same direction as the ions.

Figure 6 shows the axial and lateral magnetic fields experienced by the ions as they move through the shield. While B_A is largely unchanged, B_L has been reduced by a factor of 50, so the effect of the magnetic field on the ion motion has been reduced by a factor of 50.

As the magnetic potential field distribution external to the shield structure is not changed to any large degree, the magnetic circuit is also unaffected by the presence of the shield. In other words there is very little magnetic coupling of the shield with the magnetic circuit, so the magnetic circuit will function normally even with the shield structure in close proximity.

It is highly likely that a much simpler shield structure will work just as well as the example shown and could be as simple as a series of parallel plates with aligned apertures. The high permeability material could be mild steel (μ_r = 1000 - 1500) which is inexpensive, and the low permeability can be any non-magnetic metal (e.g. aluminium, copper, stainless, steel etc) or even just free space.

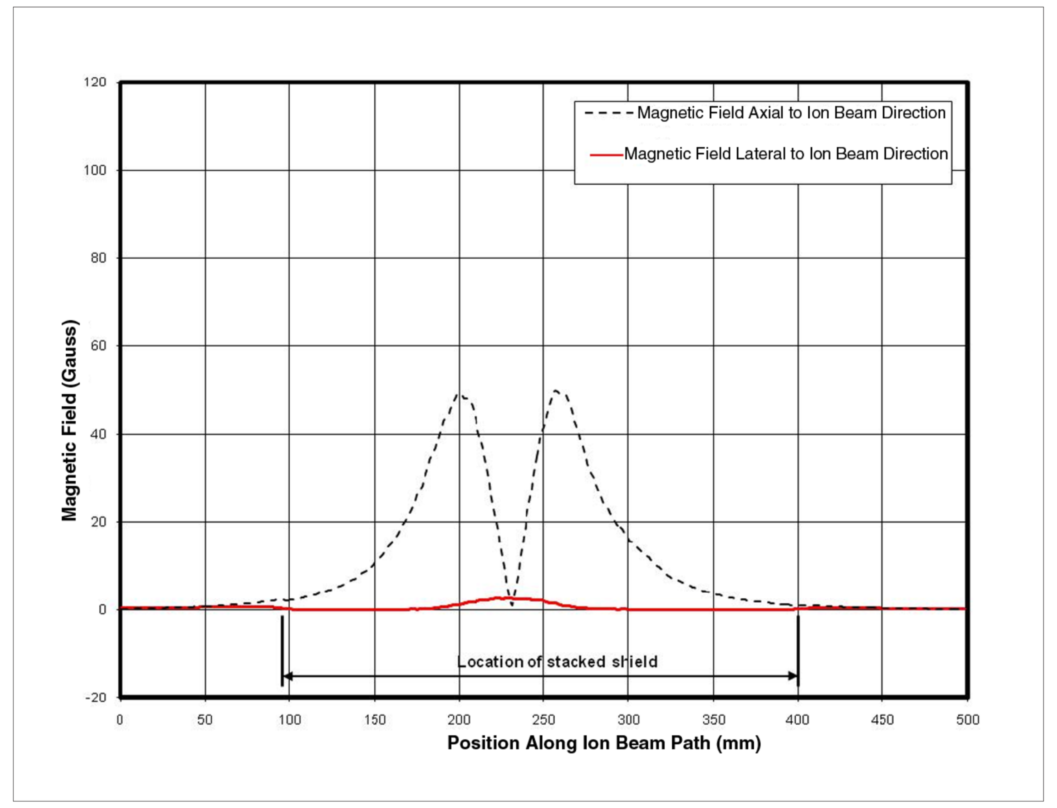

Figure 6. Magnetic field seen along the ion path with alternating permeability shield in place. Shown are the axial component of the magnetic field, BA, and the lateral component, BL, is shown in red.

Conclusions

By fabricating a magnetic shield in the form of a stack of alternating high and low magnetic permeability materials, it is possible to create a magnetic shield that re-aligns the magnetic field within the shield structure to be parallel to the direction of the ion motion without significant disruption to the surrounding magnetic potential distribution.

This approach has the following practical benefits:

- Greatly reduces the influence of the magnetic field on ion motion
- Does not magnetically couple with a nearby magnetic circuit which can adversely affect its operation
- Does not create more intense magnetic fields at the entrance and exit of the shield
- Does not spread the magnetic field into larger regions of ion-optical system.

NOTE: The above description of the analysis of magnetic fields is described in a US provisional patent application (2010).

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