Magnetic Stray Field Considerations for Medical Products

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INTRODUCTION

With the advancement of rare earth magnetic materials an increasing number of medical devices are incorporating magnetic technology. In this article, we will discuss the magnetic moment, the design of magnetic devices, how to control stray fields and magnetic field shaping. We will also discuss some safety precautions in various scenarios such as safety for patients with medical implants; the impact of stray magnetic fields on sensitive instruments; the selection of appropriate shielding materials; attractive forces of ferrous metal objects in the vicinity magnet or magnetic assembly and safety guidelines for air shipment of magnets and magnetic assemblies.

MAGNETIC MOMENT

Stray field is mostly driven by the net magnetic moment of the magnets or assemblies. For a magnet, the magnetic moment is the product of its intrinsic flux density Bdi and volume (V). The equation for magnetic moment is:

$$m = \frac{B_{di}V}{\mu_0} \qquad (1)$$

If the intrinsic flux density is not readily available, the magnetic moment of a magnet can also be calculated with the residual induction Br of the material:

$$m = \frac{B_r V}{\mu_0} \qquad (2)$$

For a magnetic assembly, the net magnetic moment is the vector sum of the magnetic moments of all the magnetic components. Table 1 shows magnetic moment of some magnets and assemblies. Note that the net magnetic moment of the 125 NM torque coupler is 0. This is because torque couplers have alternating poles and usually with back iron. The magnetic moments of these components cancel each other, and the stray fields of efficiently designed magnetic torque couplers are usually very low. However, the stray field close to the coupler depends on both the net magnetic moment of the coupler and its geometry. If the torque coupler is not properly designed, then it could have higher stray field close to the coupler.

Fig.1 shows the stray field of the 125 NM coupler at 25 mm distance from the outer housing. The peak stray field is only 4.668 Gauss. Fig.2 shows the stray field of a coupler within the same envelope dimensions but not properly designed. The peak stray field reaches 30 Gauss at the same 25 mm air gap. The torque also dropped to 100 NM. A properly designed torque coupler not only improves the performance but also reduces the stray field and interference with surrounding instruments. A key element to successful magnetic design is to ensure that the useful magnetic field is directed to the working part of the magnetic circuit while the unused field is minimized or contained.

Table 1, Net magnetic moments of magnets and assemblies

Magnet/Assembly	Dimensions	Moment (Am^2)
N50 Disk mMagnet	Ø0.200"x0.100"(M)	0.056
N40 Disk Magnet	Ø1.400"x0.375"(M)	9.2
Ceramic 8 Block	2.000"x2.000"x1.000" (M)	19.78
N50 Block	3.000"x3.000"x1.500" (M)	241
Halbach Ring (OD6.0"x ID 4.0"x10.0")	Ø6.000"xØ4.000x10.000"	34.85
Torque Coupler 125 NM with N45SH	Ø5.500"x6.400"	0

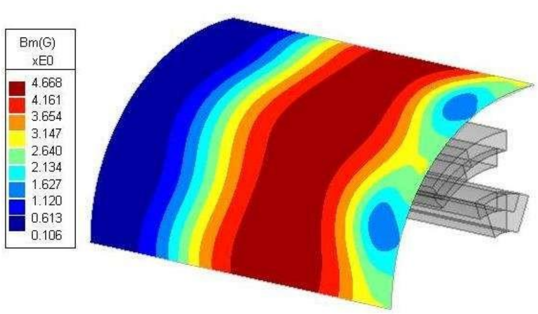

Fig.1, stray field of a properly designed torque coupler

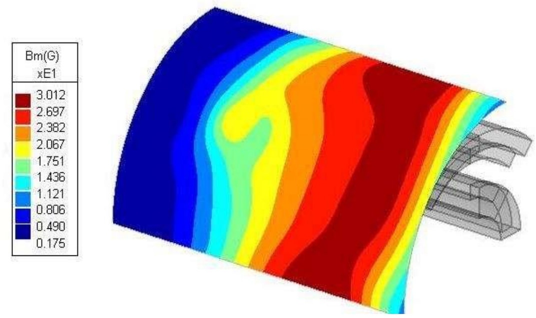

Fig.2, stray field of a torque coupler not properly designed

MAGNETIC FIELD PROFILE OF A MAGNET

The near field of a magnet or a magnetic assembly is dependent on the overall magnetic moment as well as the geometry of the magnet or assembly. For example, the magnetic field of a rectangular magnet shown in Fig.3 can be obtained from the following equations:

$$H_x = \frac{B_r}{4\pi\mu}\Big[\ln\frac{\sqrt{(L-2x)^2+(W-2y)^2+4z^2}+(L-2x)}{\sqrt{(L+2x)^2+(W-2y)^2+4z^2}-(L+2x)} + \ln\frac{\sqrt{(L+2x)^2+(W+2y)^2+4z^2}-(L+2x)}{\sqrt{(L-2x)^2+(W+2y)^2+4z^2}+(L-2x)} - \ln\frac{\sqrt{(L-2x)^2+(W-2y)^2+4(z+\lambda T)^2}+(L-2x)}{\sqrt{(L+2x)^2+(W-2y)^2+4(z+\lambda T)^2}-(L+2x)} - \ln\frac{\sqrt{(L+2x)^2+(W+2y)^2+4(z+\lambda T)^2}-(L+2x)}{\sqrt{(L-2x)^2+(W+2y)^2+4(z+\lambda T)^2}+(L-2x)}\Big] \quad (3a)$$

$$H_y = \frac{B_r}{4\pi\mu}\Big[\ln\frac{\sqrt{(L-2x)^2+(W-2y)^2+4z^2}+(W-2y)}{\sqrt{(L-2x)^2+(W+2y)^2+4z^2}-(W+2y)} + \ln\frac{\sqrt{(L+2x)^2+(W+2y)^2+4z^2}-(W+2y)}{\sqrt{(L+2x)^2+(W-2y)^2+4z^2}+(W-2y)} - \ln\frac{\sqrt{(L-2x)^2+(W-2y)^2+4(z+\lambda T)^2}+(W-2y)}{\sqrt{(L-2x)^2+(W+2y)^2+4(z+\lambda T)^2}-(W+2y)} - \ln\frac{\sqrt{(L+2x)^2+(W+2y)^2+4(z+\lambda T)^2}-(W+2y)}{\sqrt{(L+2x)^2+(W-2y)^2+4(z+\lambda T)^2}+(W-2y)}\Big] \quad (3b)$$

$$H_z = \frac{B_r}{4\pi\mu}\Big[\arctan\frac{(L-2x)(W-2y)}{2z\sqrt{(L-2x)^2+(W-2y)^2+4z^2}} + \arctan\frac{(L-2x)(W+2y)}{2z\sqrt{(L-2x)^2+(W+2y)^2+4z^2}} + \arctan\frac{(L+2x)(W-2y)}{2z\sqrt{(L+2x)^2+(W-2y)^2+4z^2}} + \arctan\frac{(L+2x)(W+2y)}{2z\sqrt{(L+2x)^2+(W+2y)^2+4z^2}} - \arctan\frac{(L-2x)(W-2y)}{2(z+\lambda T)\sqrt{(L-2x)^2+(W-2y)^2+4(z+\lambda T)^2}} - \arctan\frac{(L-2x)(W+2y)}{2(z+\lambda T)\sqrt{(L-2x)^2+(W+2y)^2+4(z+\lambda T)^2}} - \arctan\frac{(L+2x)(W-2y)}{2(z+\lambda T)\sqrt{(L+2x)^2+(W-2y)^2+4(z+\lambda T)^2}} - \arctan\frac{(L+2x)(W+2y)}{2(z+\lambda T)\sqrt{(L+2x)^2+(W+2y)^2+4(z+\lambda T)^2}}\Big]$$

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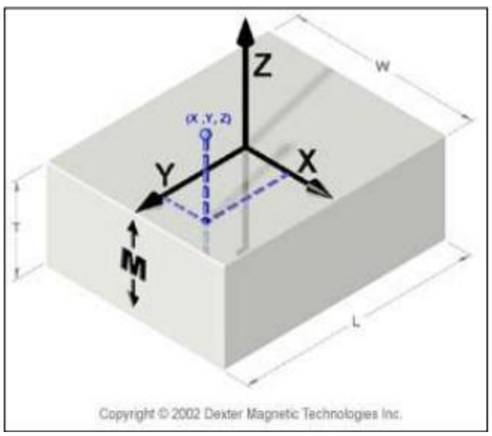

Fig.3, Rectangular magnet

These equations demonstrate that the magnetic field is dependent on the geometry of the magnet as well as its magnetization. As the field point moves further away from the magnet, the impact of magnet geometry decreases. The magnet can be viewed as a point source with the same magnetic moment and orientation as the magnet. Its magnetic field can be calculated from this equation with only the magnetic moment and the spatial coordinates of the field point:

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi}\frac{3\hat{\mathbf{r}}(\hat{\mathbf{r}}\cdot\mathbf{m})-\mathbf{m}}{|\mathbf{r}|^3}.$$

(4)In cylindrical coordinates as illustrated in Fig. 4, we can get the axial field and radial field using the following equations:

$$B_x = \frac{\mu_0 M}{4\pi}\left(\frac{3\cos^2\theta-1}{l^3}\right) \quad (5a)$$

$$B_r = \frac{\mu_0 M}{4\pi}\left(\frac{3\cos\theta\sin q}{l^3}\right) \quad (5b)$$

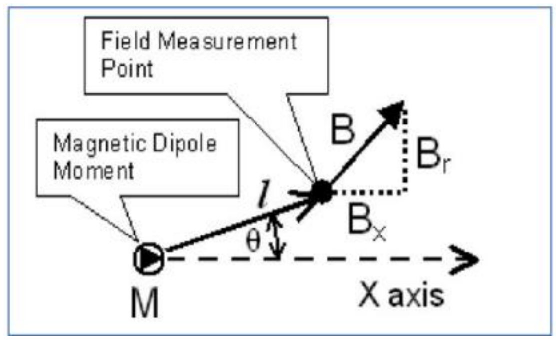

Fig.4 Magnetic fields generated by a magnetic moment

The peak on-axis stray field is when the angle θ is 0° and can be written as:

$$Bx = \frac{\mu_0 M}{2\pi l^3} \quad (6)$$

For example, for a N40 magnet with diameter of 25.4 mm and length of 10.16 mm, the magnetic moment is 5.055 Am2 . The maximum stray field calculated from equation 6 as well as from Boundary Element Analysis (BEA) model are shown in Fig.5. When the distance from the magnet is at least five inches (5 times of the maximum magnet dimension), the stray field calculated from equation 6 matches well with the computer simulation using BEA modeling software.

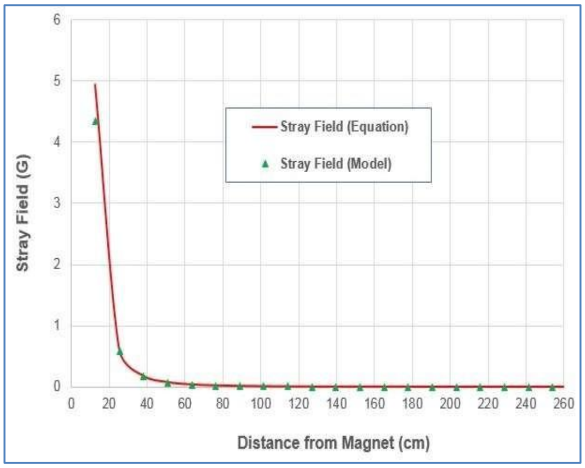

Fig 5, Stray field of a N40 magnet with Ø25.4 x 10.16 mm

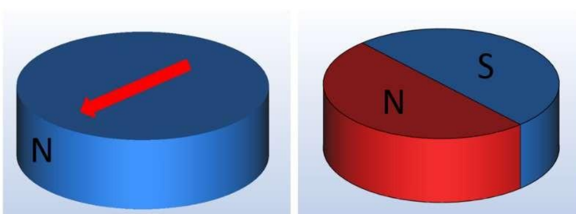

Fig.6, Diametrical vs 2-pole on one face

Another method is to design in a reverse magnetic moment to reduce the net magnetic moment. For example, the Halbach dipole in table 1 has a net magnetic moment of 34.85 Am^2. To reduce the stray field profile, we can add a redundant magnet outside the Halbach ring to reduce the net magnetic moment as shown in Fig. 7. The net magnetic moment decreases from 34.85 Am^2 to only about 0.2 Am^2 (99% reduction). The maximum stray field at 7 feet drops from 0.00785 Gauss to only 0.00034 Gauss (96% reduction).

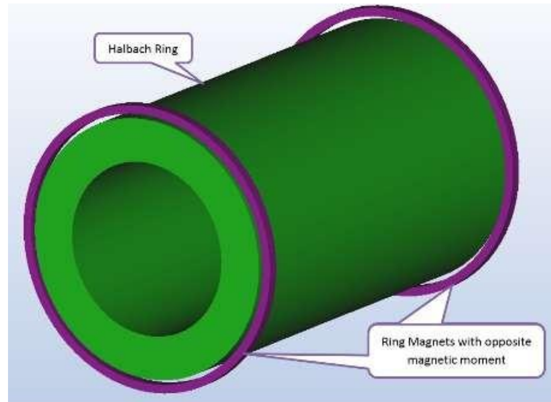

Fig. 7, Halbach ring with magnet to reduce net magnetic moment

MAGNETIC FIELD SHAPING

As mentioned earlier, Gauss's law on magnetism tells us that magnetic flux lines are closed loops and must be continuous between North and South poles. The flux lines must find way to go back to their origin and they can't be stopped, but the magnetic flux can be redirected by magnetic field shaping. Magnetic field shaping can generate high magnetic field in the volume of interest (the work zone) and reduce the stray field. One way to shape magnetic field is to use highly permeable soft ferromagnetic materials to direct the stray magnetic flux and focus the field in the work zone. For example, the beam bending magnets in a typical spectrometer can be as simple as two magnets as shown in Fig.8. By adding a steel yoke and pole pieces, the magnetic field in the work zone is stronger and the stray field is much weaker than the simple design with just the magnets.

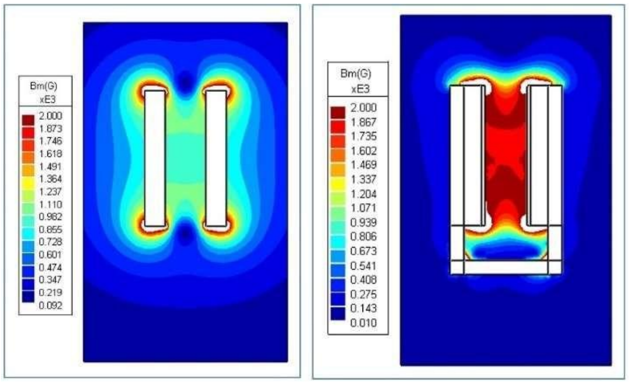

Fig. 8, magnetic field from a spectrometer dipole (picture on the left is a simple design with two magnets. the picture on the right is a design with pole pieces and a yoke)

Another commonly used method is the superposition of magnets1 as shown in Fig.9. Magnetic fields from the magnet segments combine in the work zone but cancel each other on the outside, thus minimizing the stray field while producing a magnetic field approximately three time stronger than the same structure with only two magnets.

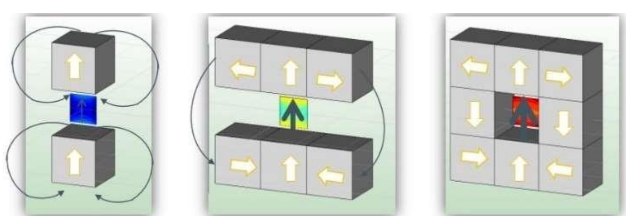

Fig. 9, illustration of magnet superposition Depending on the applications, soft magnetic materials and magnet superposition can be combined to maximum the magnetic field in the work zone and minimize the wasted stray fields.

STRAY FIELDS AND ACTIVE MEDICAL IMPLANTS

Electromagnetic interference can pose a danger to people with pacemakers and implantable cardioverterdefibrillators (ICDs). In terms of static (DC) magnetic fields, the consensus is that these devices should be able to operate as intended when exposed to fields less than 5 Gauss.2

IMPACT ON SENSITIVE INSTRUMENTS

Stray magnetic fields can have an adverse impact on instruments or devices that incorporate permanent or electromagnetic components. The stray magnetic fields can be static magnetic fields and alternating magnetic fields. The former includes non-periodic magnetic fields generated by permanent magnets, DC electromagnets or superconducting magnets, and geomagnetism. Both types can interfere with magnetic sensing devices and sensitive electronics.

For example, surgical robots include an array of magnetic sensors, holding magnets and motors. The sensors typically measure the presence of a tool, linear or rotary position. The stray magnetic fields between the various components can introduce error on the magnetic sensing devices. Careful consideration when designing these components is important.

Stray magnetic fields can impact instruments that utilize electron or charged particle beams. Mass spectrometers and instruments that include deflection yokes can be impacted.

Implantable medical devices that include magnets can introduce noise in MRI images. The impact of stray fields produced by magnetic implants on imagery is an important design consideration.

SELECTION OF APPROPRIATE SHIELDING MATERIALS

Several parameters need to be considered when selecting magnetic shielding materials. The most critical is determining the strength or flux density of the magnetic field to be shielded. Other factors include the shield geometry, required attenuation, and mechanical properties. Once the field requirements have been determined, either by direct measurement with a gauss meter or by CAD modeling, the appropriate magnetic shielding alloy can be selected. Finally, the method of fabrication and subsequent annealing needs to be planned. The ability to carry magnetic lines of flux is called permeability, and in a magnetic shield, the degree of permeability is dimensionless in the centimeter-gram-second (cgs) system and expressed numerically. The standard is free space or air, which has a permeability value of one. Typical shielding materials range in permeability from 200-350,000.

Mumetal is a nickel–iron soft ferromagnetic alloy with very high permeability, which is used for shielding sensitive electronic equipment against static or low-frequency magnetic fields. It has several compositions.

One such composition is approximately 77% nickel, 16% iron, 5% copper, and 2% chromium or molybdenum.3 The important properties of Mumetal are the high permeability and resistivity and low loss in low fields, and its good mechanical properties for easy fabrication.4 The effectiveness of Mumetal shielding decreases with the alloy's permeability, which drops off at both low field strengths and, due to saturation, at high field strengths .

In applications where higher fields are present, shields can consist of multilayer shields to distribute and provide higher flux carrying capability.

For magnetic shielding applications involving strong magnetic fields, and requiring a moderate amount of attenuation, a medium permeability alloy known in the magnetic shielding industry as Alloy 49 is used. This material is used for stronger magnetic fields because while its permeability is not as high as Mumetal’s, the saturation induction of Alloy 49 is double that of Mumetal. When saturation occurs in a magnetic shield, the permeability approaches one and affectively that of free space. In other words, the magnetic shielding effect of the material no longer exists.

In severe cases, where high magnetic fields exist, and weight is a concern, low permeability material such as 2V Permendur 49(Hiperco 50A) can be used to prevent saturation. If weight is not a concern, low carbon steel can be used. While the materials have a low initial permeability, they exhibit the ability to withstand strong magnetic fields without saturating.

GENERAL SAFETY CONSIDERATIONS

In some cases, large permanent magnets and assemblies develop strong magnetic fields with very high gradients. Although the device should be designed to focus the strongest magnetic field within the working area, some magnetic fields will inevitably leak outside the working space. In these cases, extreme precaution should be taken when handling or otherwise being near the magnets because of the following risks5:

• The device poses a health and safety risk to people with pacemakers, implantable cardioverter defibrillators, and other non-static (actively operating) implanted medical devices because they may interfere with the operation of those devices and/or cause them to malfunction, possibly resulting in injury or death.

• The device poses a safety risk when handling it because it can pinch fingers, hands, or other body parts that get between the magnet and another magnet or between the magnet and metal, possibly resulting in injury.

• The device poses a safety risk because it strongly attracts steel and other materials containing iron and nickel, such as tools, lab instruments, and personal items such as key chains and belt buckles. These items can be pulled forcefully to the device and can cause injury to someone holding the device or to someone who is near the device. Also, objects pulled to the device can injure the device itself.

• The device poses a risk of damage to electronic equipment, such as displays and monitors, damage to or disruption of data stored on magnetic media, such as hard drives and credit cards, and damage to magnetic recording devices. The device can also damage delicate instruments and watches.

MAGNETIC FIELD SHIELDING FOR AIR SHIPMENT

During the design phase, leakage fields and subsequent means of transporting the product need to be considered. If magnets and assemblies need to be shipped by air freight, the stray fields must be managed according to International Air Transport Associations (IATA)regulations. According to IATA “Dangerous Goods Regulations”, a package of magnetic material can be handled based on the following categories6.

1. If the maximum field strength measured at 7 feet is less than 0.002 Gauss, then the package is not considered magnetized material or dangerous goods. It can be shipped by air as a regular package

2. If the maximum field strength measured at 7 feet (2.1 m) is over 0.002 Gauss but less than 0.00525 Gauss measured at 15 feet (4.6 m), then follow the IATA packaging instruction 902 and mark the package "Magnetized Material"

3. If the maximum field strength measured at 15 feet (4.6 m) exceeds 0.00525 Gauss, then the package can't be shipped by air.

4. The package can be shielded with soft magnetic materials to reduce the magnetic field strength in order to conform to IATA regulations for air freight.

Special permits are required to transport packages that produce more than 0.00525 Gauss measured at 15 feet (4.6 m) if shielding fails to meet the regulations.

As discussed earlier, the stray field is mainly driven by the net magnetic moment of the magnet or assembly. and the maximum stray field can be calculated by the equation 6. Using this equation, we evaluate the maximum stray field of the magnetic items in table 1. As shown in table 2, if the net magnetic moment of a package is below 9.2 Am2 , then the package can be shipped by air as a regular package. If the net magnetic moment is under 241 Am2 , then the maximum stray field at 15 feet is about 0.00495 Gauss. The package can be shipped by air as "Magnetized Materials". Any package with net magnetic moment of over 241 Am^2 shouldn't be shipped by air without further shielding with the soft magnetic materials referenced above.

Magnet/Assembly	Dimensions	Moment (Am^2)	Stray Field at 7 feet (G)	Stray field at 15 feet (G)
N50 Disk mMagnet	Ø0.200"x0.100"(M)	0.056	0.00001	0.00000
N40 Disk Magnet	Ø1.400"x0.375"(M)	9.2	0.00199	0.00019
Ceramic 8 Block	2.000"x2.000"x1.000" (M)	19.78	0.00427	0.00041
N50 Block	3.000"x3.000"x1.500" (M)	241	0.05205	0.00495
Halbach Ring (OD6.0"x ID 4.0"x10.0")	Ø6.000"xØ4.000x10.000"	34.85	0.00753	0.00072
Torque Coupler 125 NM with N45SH	Ø5.500"x6.400"	0	0.00000	0.00000

Table 2, Stray field of various magnetic moments

If the package contains more than one unit, then the units should be arranged such that the magnetic moments cancel each other to reduce stray fields. These recommendations are for reference only. The stray field must be verified with a Gaussmeter and a magnetic field probe.

SUMMARY

Incorporating magnetic products into medical device applications involves multiple design considerations. Stray magnetic fields can affect sensitive instruments, medical implants, general safety, transportation requirement and overall compliance.

Dexter's long track record of creating unique solutions spans a wide range of industries and applications.

Whether your design has specific performance characteristics, size constraints, or operated in a special environment, you can be assured that

Dexter can provide the ideal and safe solution.

REFERENCES

(1) United States Patent:5635889 by Richard Stelter

(2) JA Leavey, Penn State University, Environmental Health and Safety Guidelines, Page 5

(3) Jiles, David(1998). Introduction to Magnetism and Magnetic Materials. CRC Press. p. 354. ISBN 978-1-412-79860-3

(4) Richard M. Bozorth (1983) Ferromagnetism. IEEE Press Classic Reissue p. ISBN 0-7803-103202

(5) Dexter (2016) Safety Guidelines for LifeSepTM 1000SX Assemblies (2906027-1)

(6) IATA - 2021 Dangerous Goods Regulations Manual. Product Number 9065-62

Authors

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Mr. Li received a BS degree in Physics from Shandong University (Jinan, China) in 1990; MS degree in Materials Science & Engineering from CISRI (Beijing, China) in 1993 and MSEE from University of Kentucky in 1999. Mr. Li's work experience includes three years as a sales engineer on soft magnetic materials and components with a focus on amorphous and nanocrystalline materials; and 21 years as application engineer on permanent magnets and applications.

Since graduation from the University of Kentucky, Mr. Li worked as an application engineer at Crumax Magnetics and Vacuumschmelze before joining Dexter in 2001.

Mr. Li is currently a senior magnetics engineer at Dexter Magnetic Technologies. He has been a long time IEEE member, has co-authored multiple papers and holds five patents.

Mike Schilling

Mike Schilling (BSEE'88) received his degree in electrical engineering from the University of Illinois at Chicago in 1988.

After graduation, he started his 33-year career at Dexter Magnetic Technologies as an Application Engineer. In 1992, Mike moved into a commercial role at Dexter. Mike was able to gain market knowledge and supported multiple industries in the commercial role.

In 2020, Mr. Schilling became the Medical Market Manager at Dexter. He is a 35-year member of the IEEE, has coauthored multiple papers and holds two patents