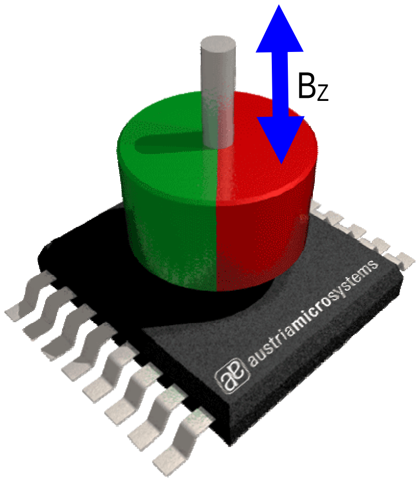
1 General Description

This document provides a detailed explanation of the magnetic field calculation principle in the AS5000 series magnetic encoder ICs along with an exemplification of magnetic properties of magnets suitable for rotary angle measurement. In particular, this document describes ways to achieve good linearity performance even beyond the recommended gap of <2mm between magnet and encoder IC.

2 The Rotary Angle Measurement Principle



The AS5000-series magnetic sensor circuits are using integrated lateral Hall sensors in standard CMOS technology. Lateral Hall elements are sensitive to the magnetic field component B_Z perpendicular to their surface. This means they are only sensitive to magnetic fields vertical to the IC.

The proper magnet for rotary angle measurement must be rotating over the center of the IC and be magnetized with the north and south poles in the horizontal plane (Fig. 1). The vertical field B_z measured along a certain radius must be sinusoidal when the magnet is rotated over 360°.

Furthermore, to achieve best accuracy, the vertical field B_z should have a wide linear range between the two poles (Fig. 2).

Fig. 1: Correct magnet placement for rotary angle measurement

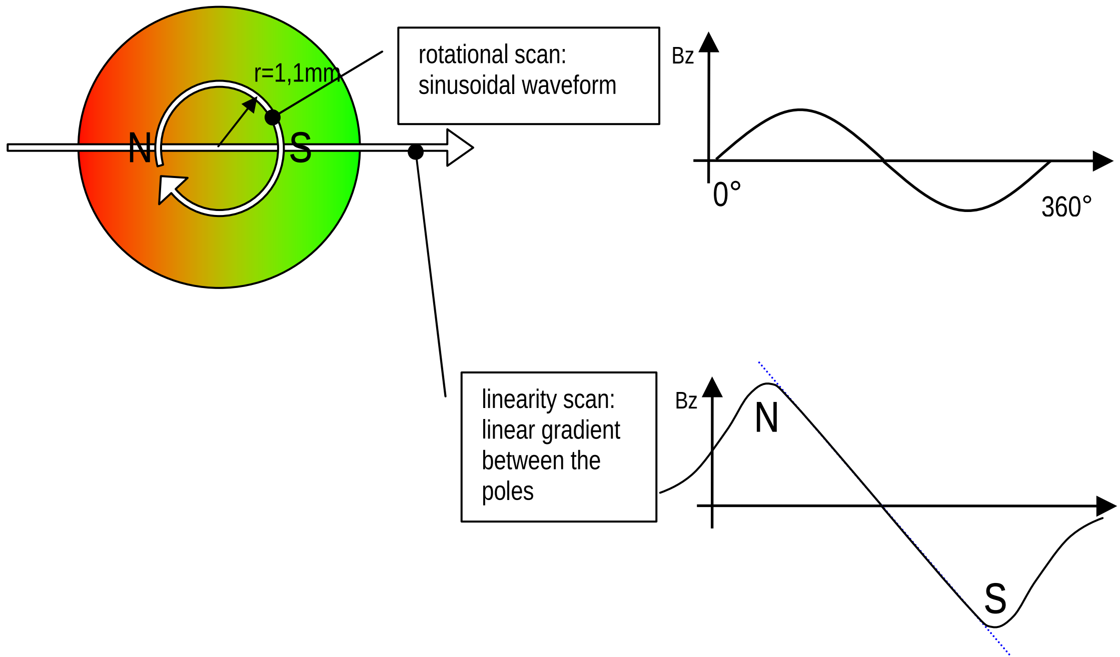


Fig. 2: Key magnet parameters: sinusoidal output and linear range

2.1 Calculation of the Angle

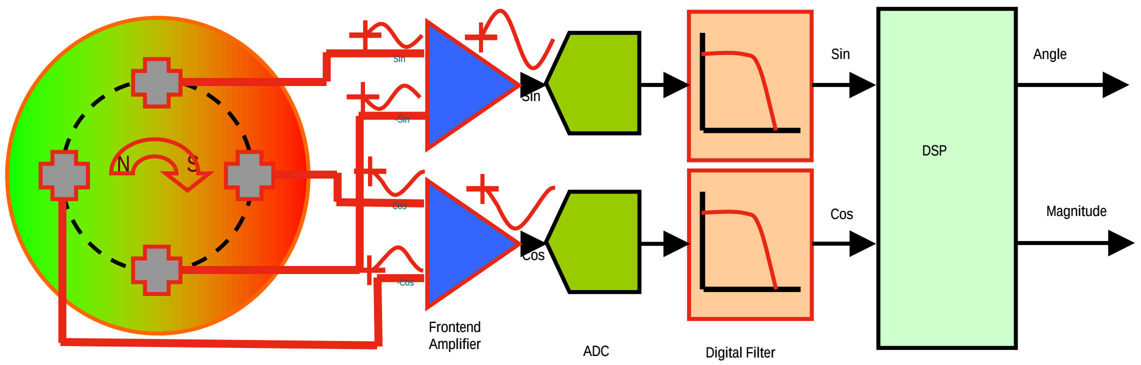


Fig. 3: Angle measurement block diagram

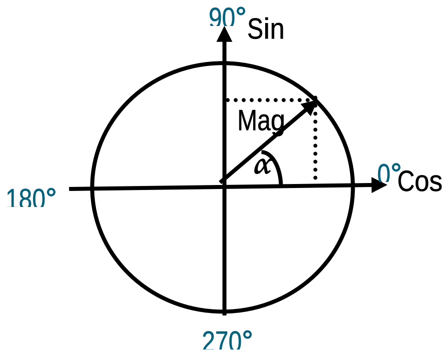


Fig. 4: Rectangular and polar coordinate system

Fig. 3 shows the basic building blocks for angle measurement. The Hall sensors are arranged in a circle, 90 degrees apart from each other. Due to this arrangement, the Hall sensor signals generated from a rotating magnet are sin(x), cos(x), -sin(x) and –cos(x). Opposite Hall sensor signals are combined by differential amplification, generating sin(x) and cos(x) signals of double amplitude:

$\sin(x) - [-\sin(x)] = 2\sin(x)$

$\cos(x) - [-\cos(x)] = 2\cos(x)$

These signals are then digitized by A/D-converters and fed to a dedicated DSP performing a vector coordinate transformation:

any two-dimensional position can be represented in two different ways (Fig. 4):

- as X- and Y- coordinate in a rectangular coordinate system
- as a vector with phase and length in a polar coordinate system

The coordinate transformation by the DSP converts the rectangular coordinates Sin(x) and Cos(x) into the polar coordinates angle and magnitude (see Fig. 3).

The angle information is proportional to the rotating angle of the magnet and the magnitude information is proportional to the magnetic field strength.

This magnetic field strength is influenced by the following factors:

- the gap between magnet and IC surface: the smaller the gap, the stronger the magnetic field
- the magnetic strength (remanence B_r) of the used magnet material: recommended= rare earth magnets: NdFeB or SmCo
- the type of magnetization of the used magnet: diametric or one face two-pole magnetization
- the temperature of the magnet: magnetic field decreases with rising temperature

2.2 The Automatic Gain Control (AGC)

The underlying principle of coordinate transformation also suggests that the angle information is independent of the magnetic field strength! In other words, if the magnet is locked at a certain angle and at the same time the distance between magnet and IC is changed, both the Sin(x) and the Cos(x) amplitude will change simultaneously so after coordinate transformation only the length of the vector (= the magnitude) will change but the angle will remain unchanged.

This effect enables a very accurate angle output despite temperature changes of the magnet as well as vertical distance changes.

In practice however, a weak magnetic field (e.g. due to a large vertical gap or a weak magnet material) incurs a poorer signal to noise ratio compared to a strong magnetic field. As a result, the higher noise on the sin(x) and cos(x) signal inputs of the DSP will lead to more jitter of the angle and magnitude outputs.

To tackle this effect, an automatic gain control (AGC) is implemented in the AS5000 series encoders: it stabilizes the sin(x) and cos(x) signals by changing the sensitivity of the Hall sensor front-end, trying to maintain a constant magnitude output.

This way, the magnetic field may change over a wide range (typ. ~35….65mT[1)]) while the magnitude output of the DSP will remain at a stable value.

1) magnetic field strength is often referred to in other measurement units as well:

1 mT (milliTesla) = 10G (Gauss) = 796A/m (amperes per meter) = 0.796kA/m (kiloamperes per meter)

2.3 Z-Axis Range Indication: RED / (YELLOW /) GREEN Indicators

The recommended operation range for the AS5000-series encoders is where the AGC remains within its regulation limits and the magnitude is at the regulated set point. This is referred to as the “Green” range.
The “Green” range is usually indicated as a status bit in the serial data, as a hardware output pin or both.

Some ICs, like the AS5046, AS5045, AS5145, etc. also offer an additional range indicator, the “Yellow” range indicator. In this range, the AGC is either at the lower limit and the magnitude is <50% above the regulated set point (strong magnetic field) or the AGC is at the upper limit and the magnitude is <50% below the regulated set point (weak magnetic field).
The “Yellow” range is indicated as a combination of status bits in the serial data (see Table 1)

Finally, the “Red” range is the non-recommended range. This range is indicated, when the magnitude is >150% or <50% of the regulated set point.
For encoders having a red-yellow-green indicator, the “Red” range is indicated as a status bit in the serial data
For encoder having only a red-green indicator, the “Red” range is indicated when the IC is not in the green range (see above)

Note: using the recommended magnets, the “Red” range is never triggered with a too strong magnetic field, even when the magnet is touching the IC surface. The “Red” range is only triggered when the magnetic field gets too weak. The encoder IC will **not** suddenly stop operating in the “Red” range; rather it will continue to operate even with weak magnetic fields. The angle output jitter will increase and the accuracy will decrease as the magnetic field gets weaker.
The “Red” range is also used to indicate a missing magnet, in which case there is certainly no operation possible. The best way to distinguish a weak “red” magnet from a missing magnet is to read the magnitude information (e.g. when using the AS5046). A missing magnet will show a magnitude = 0 reading while a weak magnet will show a magnitude reading >=1.

Example: AS5046: magnetic field range indicators

Status Bits			Hardware Pins		Description
Mag INC	Mag DEC	LIN	Mag Rngn	Analog output	
0	0	0	Off	enabled	No distance change Magnetic Input Field OK (GREEN range, ~35…65mT)
0	1	0	Off	enabled	Distance increase, GREEN range; Pull-function. This state is dynamic and only active while the magnet is moving away from the chip.
1	0	0	Off	enabled	Distance decrease, GREEN range; Push- function. This state is dynamic and only active while the magnet is moving towards the chip.
1	1	0	On	enabled	YELLOW range: Magnetic field is ~ 18…35mT or ~65…97mT. The AS5046 may still be operated in this range, but with slightly reduced accuracy.
1	1	1	On	disabled	RED range: Magnetic field is ~<18mT or >~97mT. It is still possible to use the absolute serial interface in the red range, but not recommended.

Table 1: Magnetic field strength indicators

2.4 AGC and Magnitude Registers

Depending on the encoder IC, the AGC and magnitude information may be available or not. The AS5046 for example enables access to this information by reading the magnitude and AGC registers. Fig. 5 shows a graphic example of the interrelations between these two registers in respect to the magnetic field strength of the magnet (all register levels are in decimal format).
At a low magnetic field strength (below level B1 / B2) the magnitude will be <32 and the AGC will be at maximum: 255. The LIN status bit will be set (red range).
If the magnetic field strength is further increased above a magnitude value of 32, LIN will be cleared. The AGC will remain at 255 until the magnitude has reached the set point value of 63 (yellow range; level B3/B4). The angular data can still be used in the yellow range, but the noise (=jitter) will be larger than normal.
Once the magnitude is strong enough to reach a value of 63, the AGC will regulate the internal loop gain to maintain this value. Magnitude will remain at 63 and the AGC will regulate between 0 and 255 (green range; magnetic field strength between level B3/B4 and B5/B6). This is the recommended operating range
If the magnetic field strength rises further than B5/B4, the AGC can no longer regulate the loop and will be at its minimum value of 0. The magnitude value will increase (yellow range; up to B7/B8). In this range, the angular data will still be valid. Due to the rather strong field, there is no issue with noise, but the magnetic field may be more distorted than in the normal operating range which may lead to additional errors.
Above level B7/B8 the LIN alarm will be set once the magnitude has exceeded a level of 95 (red range).
As mentioned above, this condition is never triggered with the recommended magnets, even at 0mm vertical distance.

At a magnitude level of >127 the COF (CORDIC overflow) status bit will be set, indicating that the sin(x) cos(x) input data for the DSP is invalid. Again, this condition would only be triggered with very strong magnetic fields and does not occur in practice.

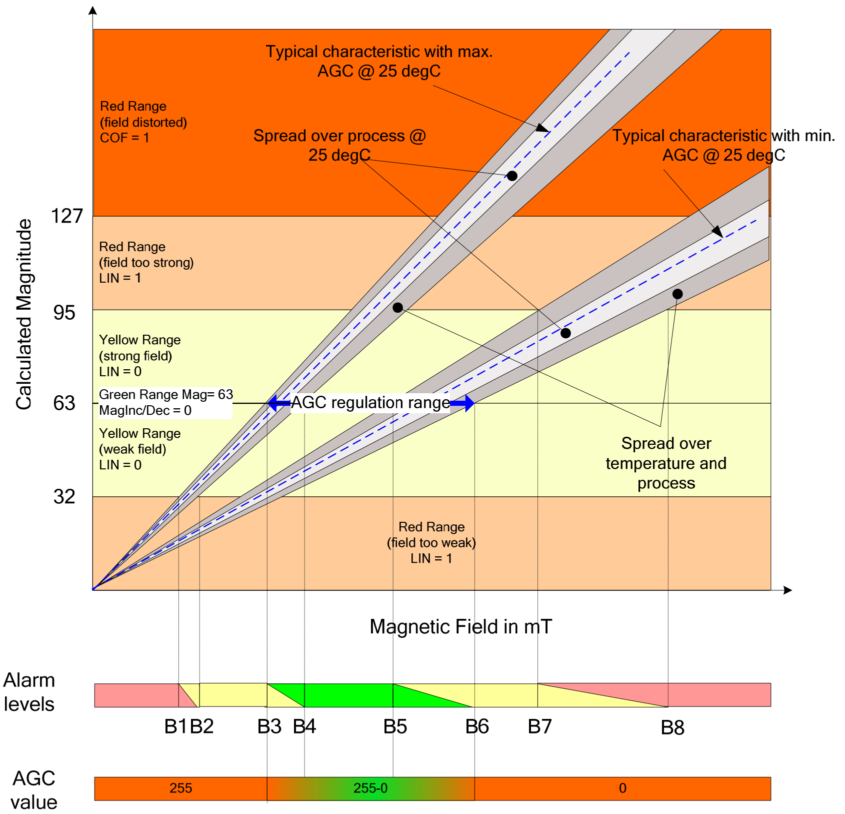


Fig. 5: Magnitude and AGC values vs. magnetic field strength

Parameter	Symbol	Min	Typ	Max	Unit	Note
Input Field tolerance level red2yellow B1 - B2	B_{r2y25}	16.77	17.95	19.33	mT	At 25°C ambient temperature
Input Field tolerance level yellow2green B3 - B4	B_{y2g25}	33.01	35.35	38.06	mT	
Input Field tolerance level green2yellow B5 - B6	B_{g2y25}	60.0	64.24	69.15	mT	
Input Field tolerance level yellow2red B7 – B8	B_{y2r25}	90.45	96.87	104.28	mT	
Input Field tolerance level red2yellow B1 - B2	B_{r2y}	15.64	17.95	22.37	mT	Over the full specified temperature range
Input Field tolerance level yellow2green B3 - B4	B_{y2g}	30.80	35.35	44.05	mT	
Input Field tolerance level green2yellow B5 - B6	B_{g2y}	55.96	64.24	80.04	mT	
Input Field tolerance level yellow2red B7 – B8	B_{y2r}	84.39	96.87	120.69	mT	

3 Types of Magnetization

3.1 Diametrically Magnetized Magnets

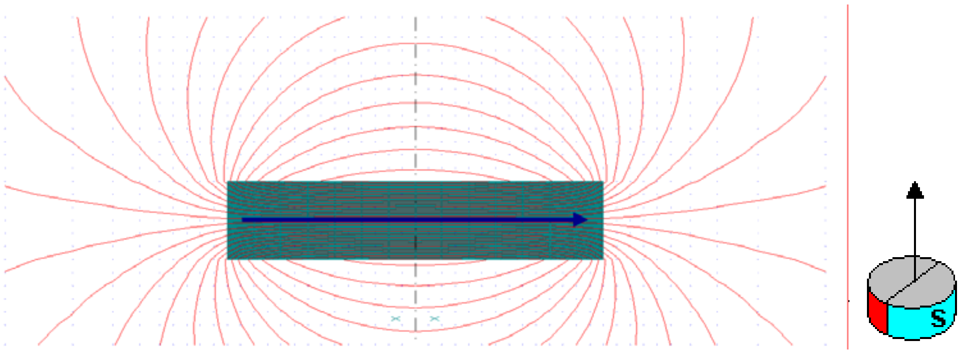


Fig. 6: Field lines and shape of a cylindrical diametrically magnetized magnet

The most common types of magnets for the AS5000 rotary encoder family are cylindrical diametrically magnetized magnets with typ. 6.0mm in diameter and 2.5mm in height. The magnet material is Neodymium-Iron-Boron (NdFeB) or Samarium-Cobalt (SmCo).
Diametrical magnets are fairly easy to simulate and understand; they offer a wide linear range and are fairly cheap.
They are an excellent choice for distances between of 0.5 to 2.0mm between magnet and IC.
At larger distances however, the linear range between the poles (see Fig. 7 and Fig. 8) decreases, causing a decrease in accuracy.

Fig. 7 shows the linearity scan of a 6.0mm diameter diametrical magnet at vertical distances of 1, 2 and 3mm (see Fig. 2 for linearity scans). It also shows a vertical line at 1.1mm, indicating the radius at which the Hall sensors are measuring the magnetic field.

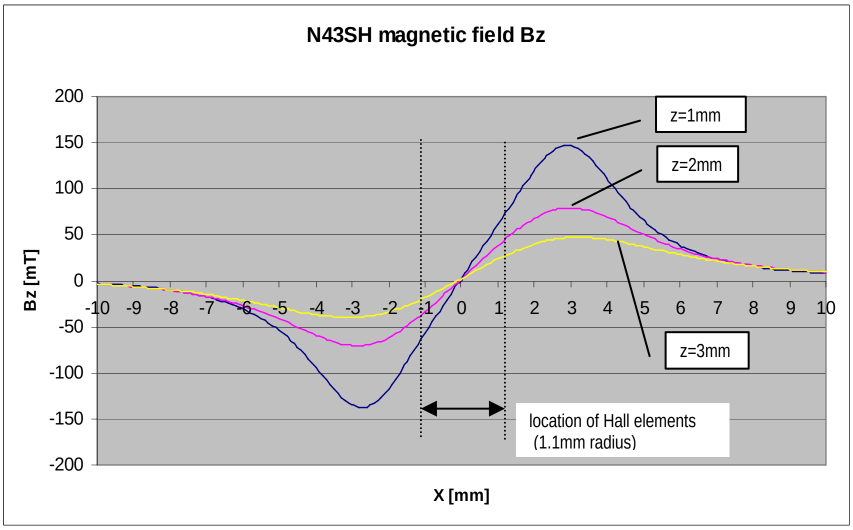


Fig. 7: Vertical field Bz of a diametrical magnet at different gaps

Fig. 8 shows a magnified view of Fig. 7 with superimposed straight lines to compare the linearity of the field. The vertical, dotted lines show the limit for each vertical distance, at which the non-linearity of the curves is exceeding the recommended limit of 5%. It shows that the linear range decreases with vertical distance, indicating less lateral movement area with increasing gap.

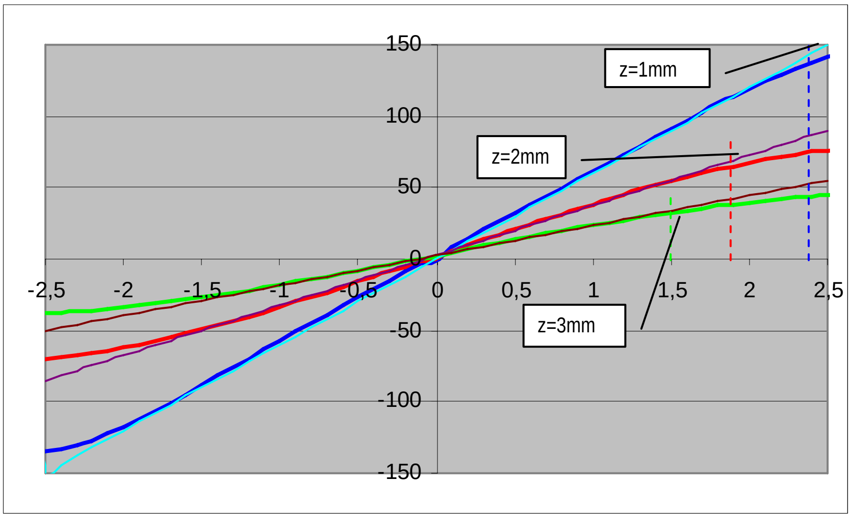


Fig. 8: Linear range at different vertical distances (magnified view of Fig. 7)

3.1.1 Diametrical Magnets: Accuracy versus Misalignment and Airgap

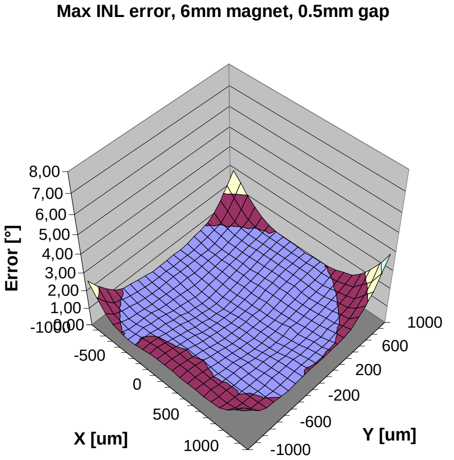


Fig. 9 shows a 3D-INL (integral non-linearity) plot of a diametrical 6mm diameter magnet at 0.5 mm airgap.
To generate this plot, the magnet is scanned in 100µm increments over a horizontal misalignment range between -1mm and +1mm in both X- and Y- direction. A perfectly centered magnet would be in the center of the bottom square, a magnet misaligned -1mm in X and +1mm in Y would be in the top corner of the graph, etc...
The vertical axis shows the worst case accuracy over a full turn at each X- and Y- displacement.
As the result shows, the accuracy is better than 1.0° even if the magnet is ~1mm off-center in any direction.

Fig. 9: 3D-INL plot of a 6mm diametrical magnet at 0.5mm airgap

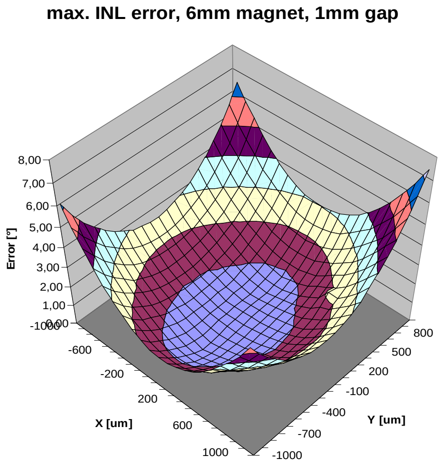


Fig. 10 shows the same magnet at a distance of 1.0mm. As the result shows, the accuracy is still good with a centered magnet (same colors = same accuracy), but the freedom of lateral movement is reduced. This is due to the linear range of the magnet which decreases with vertical distance (Fig. 8).

Fig. 10: 3D-INL plot of a 6mm diametrical magnet at 1.0mm airgap

3.2 One Face 2-Pole Magnetization

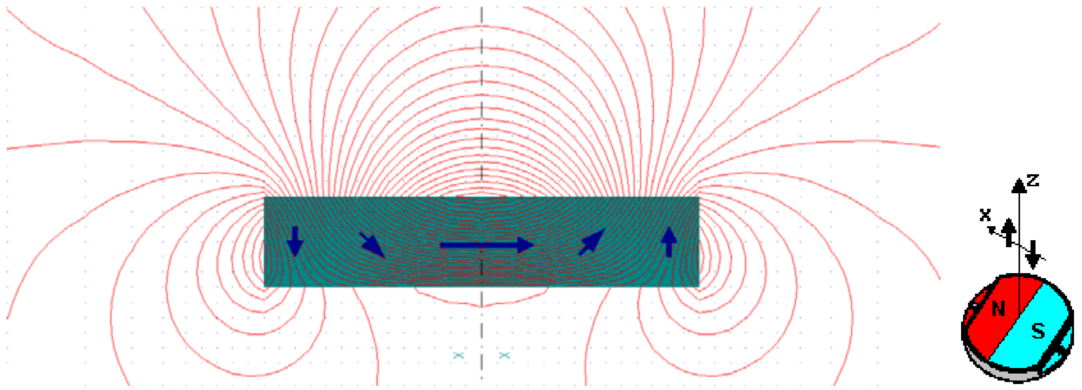


Fig. 11: Field lines and shape of a one face 2-pole magnetized magnet (courteously of Magnetfabrik Bonn, Germany)

As opposed to diametrical magnets, where the magnetic field lines enter and exit at the side of the magnet (see Fig. 6), two pole magnets magnetized at the face have, as the name suggests, both poles located at the top surface of the magnet. The back of the magnet has nearly neutral magnetic field allowing the magnet to be mounted directly on a ferromagnetic material without loss of magnetic field strength. The two-pole magnetization on the face results in about 2 times the magnetic field strength and very low magnetic stray fields at the side of the magnet which may affect other nearby sensors. These magnets can also be fabricated using injection moulding allowing the inclusion of mounting holes or other markers.

However, due to the poles on one side, the linear range between the poles is also significantly shorter compared to diametric magnets which results in about 2x larger diameter for comparable performance over lateral misalignment.
The major advantage of this magnet type is that the accuracy over vertical distance does not decrease as fast as with diametric magnets.

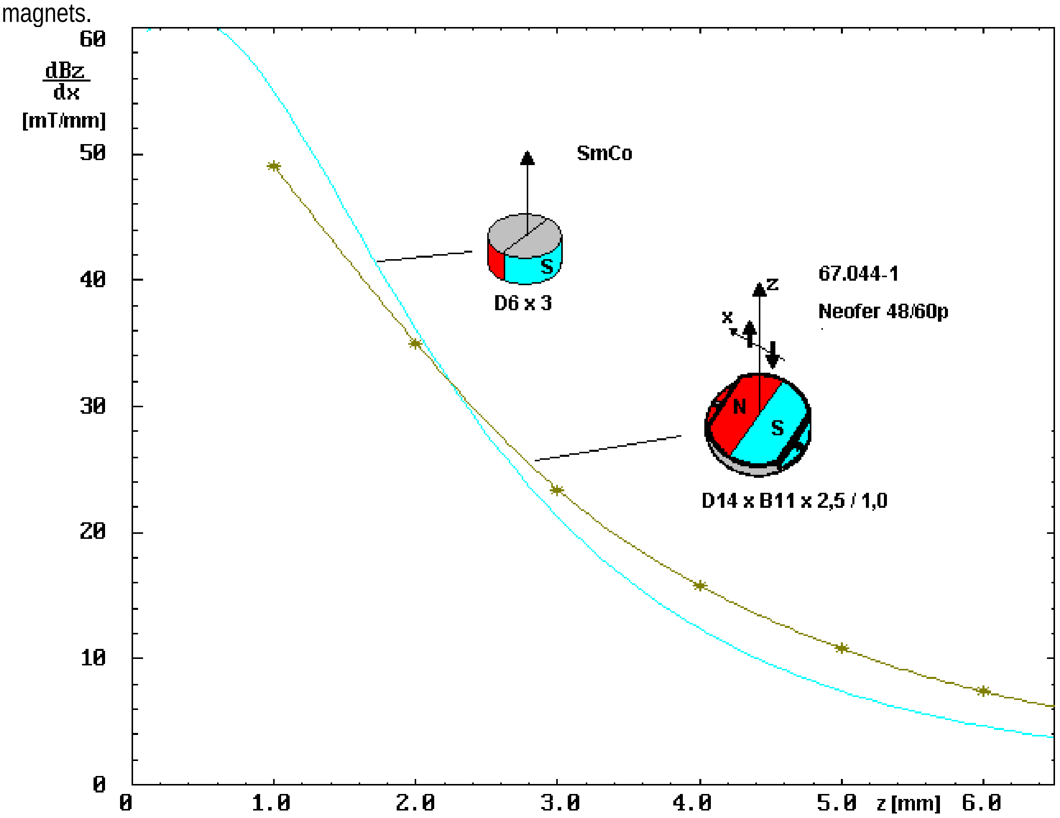


Fig. 12: Vertical field strength of diametric SmCo and 2-pole plastic bonded NdFeB magnet (courteously of Magnetfabrik Bonn)

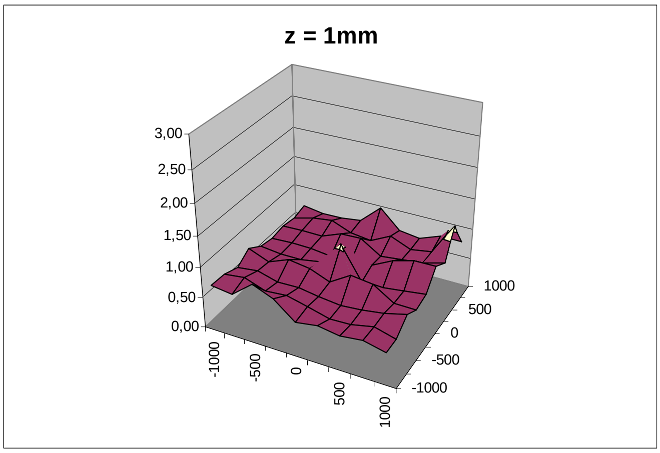
Fig. 12 shows a comparison of a diametric SmCo magnet with 6.0mm diameter and a 2-pole plastic bonded NdFeB magnet with 14mm diameter. While the SmCo magnet is stronger at small distances (<2.5mm), the 2-pole magnet performs better at larger distances.

3.2.1 One Face 2-Pole Magnets: Accuracy versus Misalignment and Airgap

Fig. 13 and Fig. 14 show 3D-INL plots (same conditions as Fig. 9 and Fig. 10) of a one face 2-pole magnet, type 67.044-1 by Magnetfabrik Bonn (www.magnetifabrik.de). As the plots show, the absolute accuracy of a centered magnet at 1.0mm airgap is comparably equal to a diametric magnet. However, the accuracy over lateral displacement is significantly improved (compare Fig. 10).

The accuracy remains at 0.5°…1.0°	at 1.0mm airgap (green range),
stays around 1.0°	at 2.0mm airgap (green range),
lies between 1.0° and 1.5°	at 3.0mm airgap (yellow range)
and is still better than 2.0° degrees	at 4.0mm airgap (red range).

See also: Fig. 17 for the red-yellow-green limits



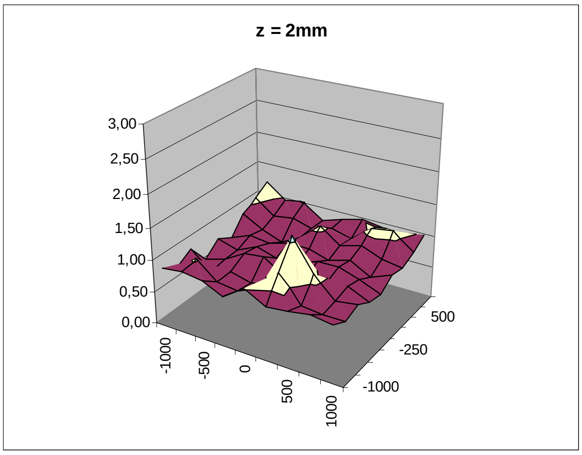


Fig. 13: 14mm diameter one face 2-pole magnet at 1.0 and 2.0 mm airgap

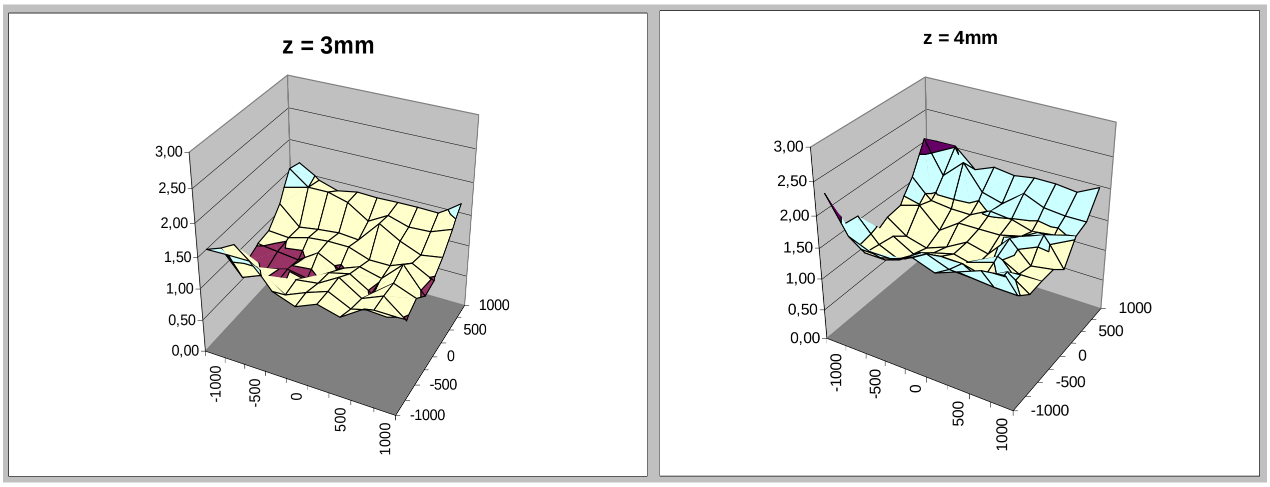


Fig. 14: 14mm diameter one face 2-pole magnet at 3.0 and 4.0 mm airgap

4 Using Stronger Diametric Magnet Material

The recommended grade for diametrical magnets is N35H with a typical remanence of 1.21Tesla.
There are stronger grades available from various magnet manufacturers (www.bomatec.ch, www.arnoldmagnetics.com, www.aic.com.hk and others) such as N48H with a remanence of 1.41 Tesla.
Using these stronger magnets, the vertical gap for the “Green” range can be increased by a few tenths of a millimeter. The decrease of linearity (see Fig. 9 and Fig. 10) however remains similar to that of weaker diametric magnets.

5 Summary: vertical range comparison of different magnets

Fig. 15- Fig. 17 show the AGC and Magnitude readings from the magnetic encoder (e.g. AS5046), obtained with different magnets. See also 2.4 for further reference. At small airgaps, the AGC value is low and tries to maintain a constant Magnitude level. As the gap increases and the magnetic field gets weaker, the AGC increases. Once it has reached its maximum of 255, the magnitude value drops with further increasing vertical distance. A red range is indicated when the magnitude is less than half of its nominal level.

5.1 Standard magnet: 6mm diameter x2.5mm, NdFeB N35H magnet

The standard magnet has 6mm diameter and 2.5mm thickness. The magnet material is NdFeB, Grade N35H (Br = typ. 1.21T)
It has the green range from 0.65 – 2.05mm. The yellow range is between 0mm (magnet touches IC surface) to 0.65mm and between 2.05 – 3.25mm. Note: these results are typical values.

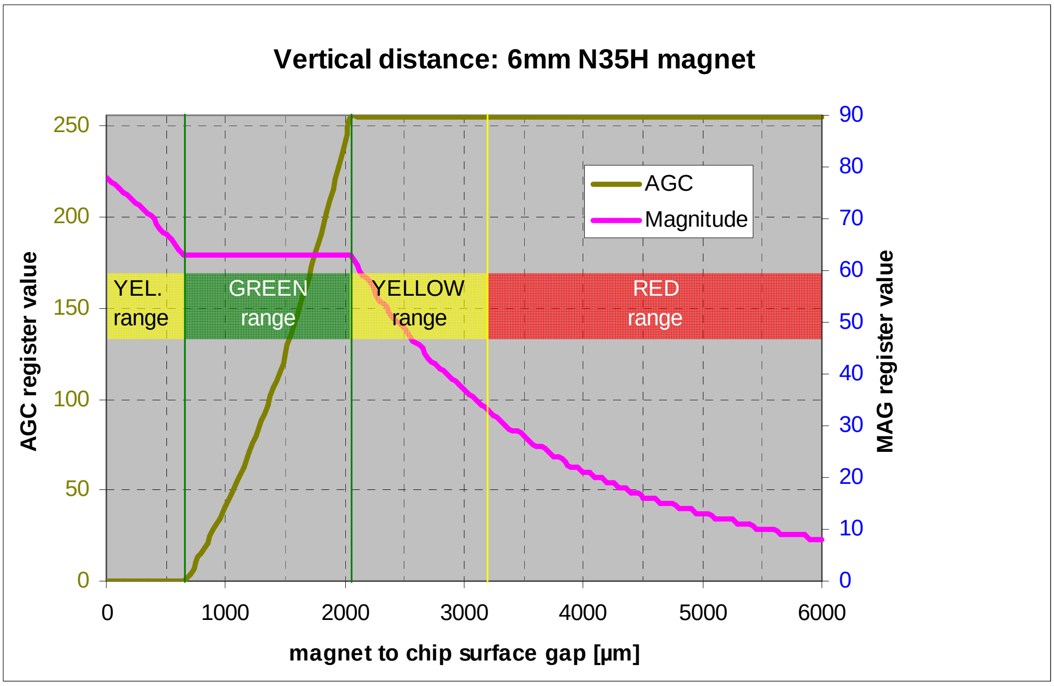


Fig. 15: typical red-yellow-green ranges of the standard N35H magnet

5.2 6mm diameter x2.5mm, NdFeB N43SH magnet

The N43SH magnet with 6mm diameter and 2.5mm thickness is about 12% stronger than the N35H magnet (Br = typ. 1.35T) It has the green range from 0.8 – 2.2mm, which allows about 0.15mm larger airgap for the same performance as the standard magnet (see Fig. 15). The yellow range is between 0mm (magnet touches IC surface) to 0.8mm and between 2.2 – 3.4mm. Note: these results are typical values.

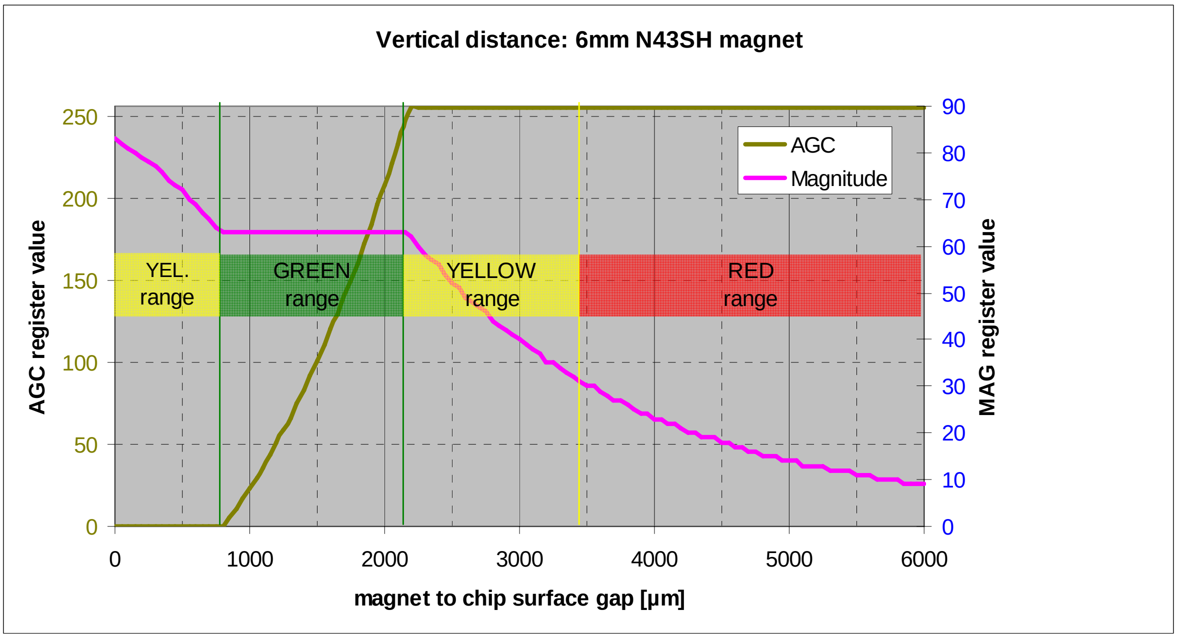


Fig. 16: typical red-yellow-green ranges of a N43SH magnet

5.3 14mm diameter x2.5mm, one-face two-pole magnet

The one-face two-pole plastic bonded NdFeB magnet (type 67044-1, supplier: Magnetfabrik Bonn) is weaker at short distances (see also Fig. 12), but the Bz field istronger at large distances. This is also reflected in the operating ranges: It has the green range from 0mm (magnet touches IC surface) – 1.7mm, which is about 0.35mm less than the standard magnet. The yellow range however, is between 1.7 and 3.4mm, a gain of 0.15mm for the upper limit compared to the standard magnet and an equal limit compared to the strong N43SH magnet. Note: these results are typical values.

As the test results show (see 3.2.1) this magnet shows the best performance at large gaps, even in the red range,

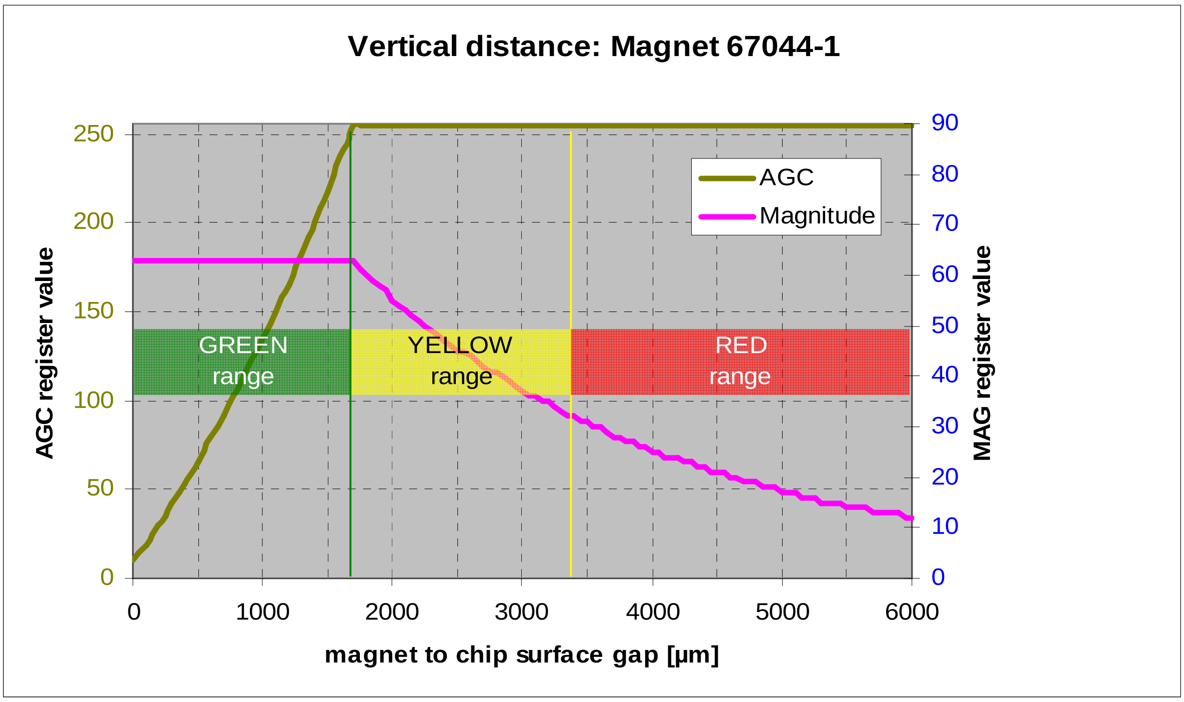


Fig. 17: typical red-yellow-green ranges of a one face two pole magnet

6 Contact

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