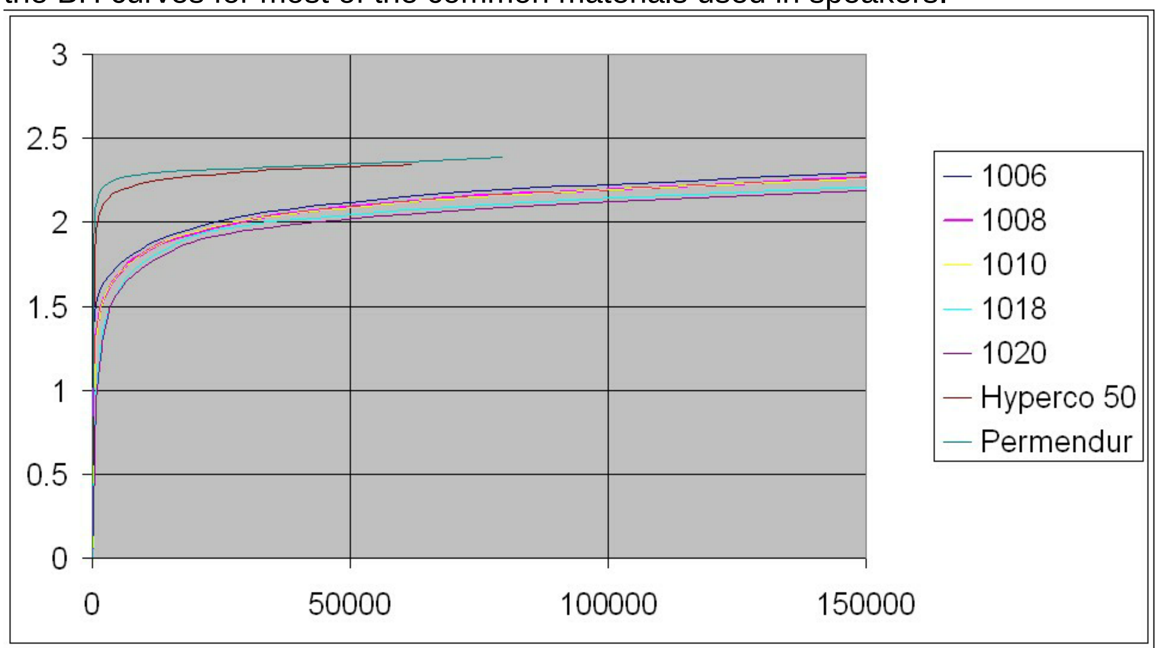
Low Reluctance Return Path Motors
An application note for STEP Technologies Patent 7,065,225

One of the most difficult problems for a speaker engineer working with neodymium motors is balancing coil diameter with gap strength. This is especially true when working with small multimedia speakers. Typically these speakers use a 19 or 25 mm coil to reduce inductance and moving mass, and thereby improve high frequency response. The problem is getting both high efficiency and high excursion from these relatively small motors.

Here is a typical design scenario:
A 25mm (diameter) motor using 24mm magnet, 25mm FPOD and a 1mm gap width (these are common dimensions for a standard 2 layer coil)
The design goal is to get 2mm of physical Xmax with the maximum possible sensitivity.

Efficiency is determined by the ratio of force (BL) to mass. For this discussion we will look at only the ratio of BL to coil mass. The "B" part of BL is the amount of magnetic strength in Teslas, that can be applied over the length of wire "L" in the voice coil. The use of FEA software (in this case Spea*DFEA*) makes it easy to calculate these values.

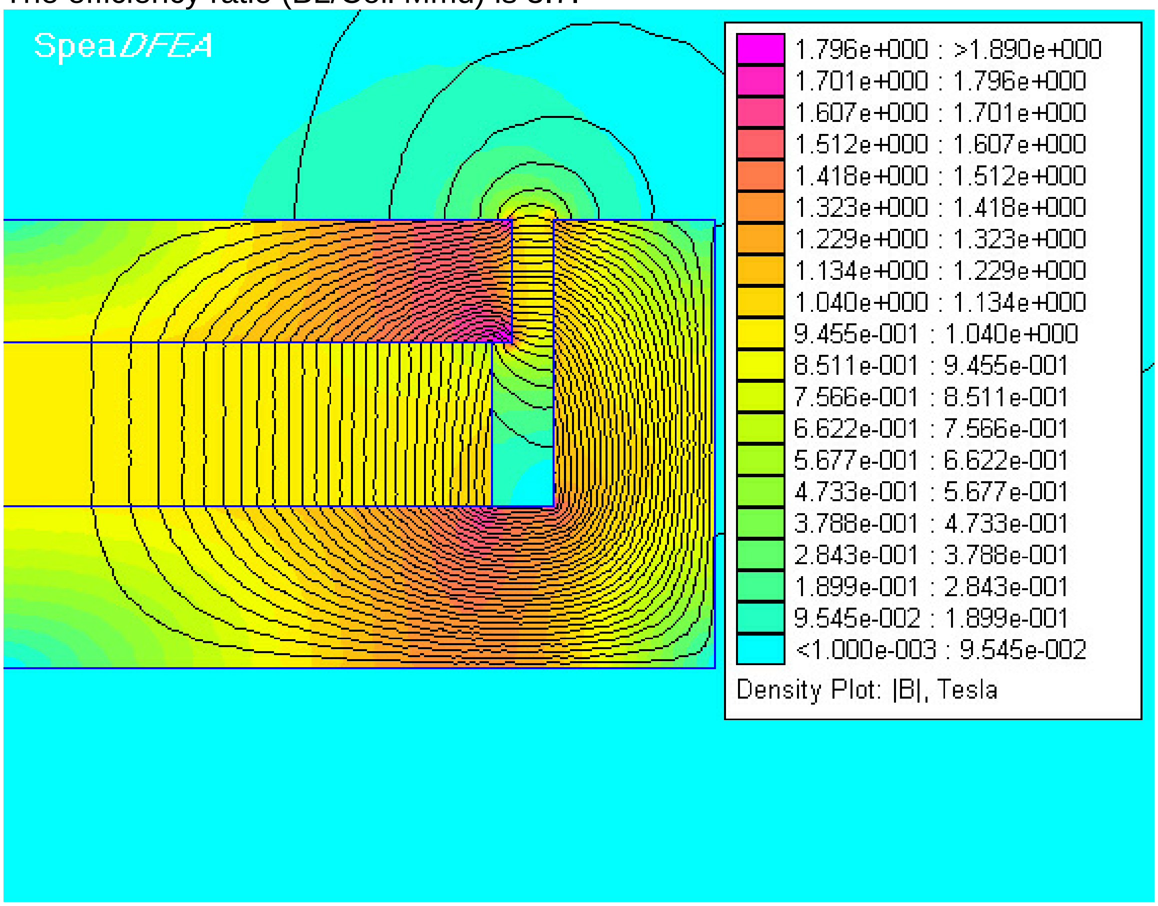
The limit for any design is usually determined by the amount of flux that can pass through the steel parts – specifically, the parts which define the magnetic gap. This maximum limit is related to the materials' BH curve. The graph below shows the BH curves for most of the common materials used in speakers.



The sharp slope on the left side of the curves is the linear region and the flat section on the right shows where the material has reached saturation and can not pass any more flux. The transition point between these two slopes is called the knee. The knee is the point where increasing the magnetic strength (or magnet size) achieves very little increase in gap strength. In the FEA plots used in the following examples, this level will be shown as areas of pink. (Note that all of these examples are using 1008 steel with a knee of 1.9 Tesla and N37 neodymium magnets. The coil material is copper, and assumes a DCR of 8 Ohms.)

Design 1

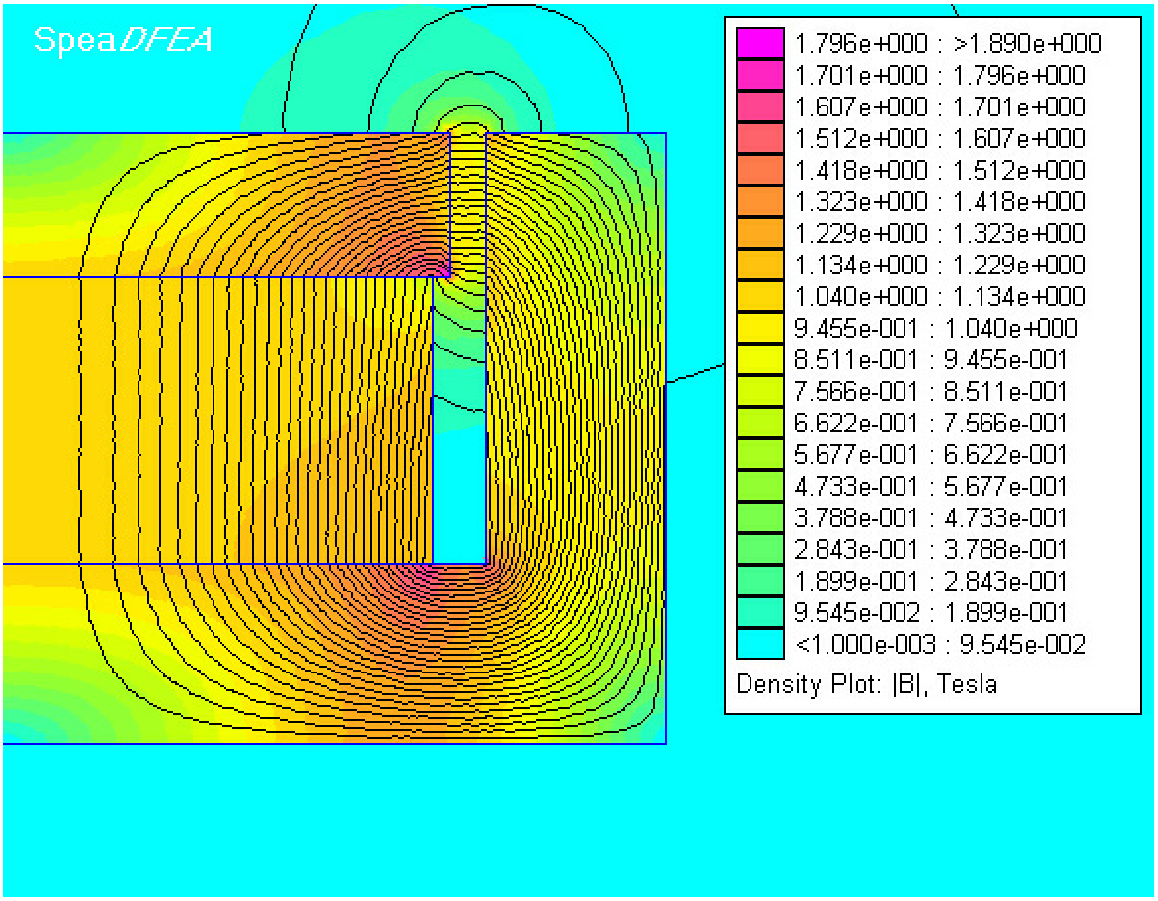
With an over-hung design we find that a 3mm thick top plate and 4mm thick magnet achieve our goal of reaching the BH knee of the steel. For a 2mm Xmax, the coil height is 7mm. This yields a BL of 4.48 and a coil mass of 1.21 grams. The efficiency ratio (BL/Coil Mmd) is 3.7.



Design 2

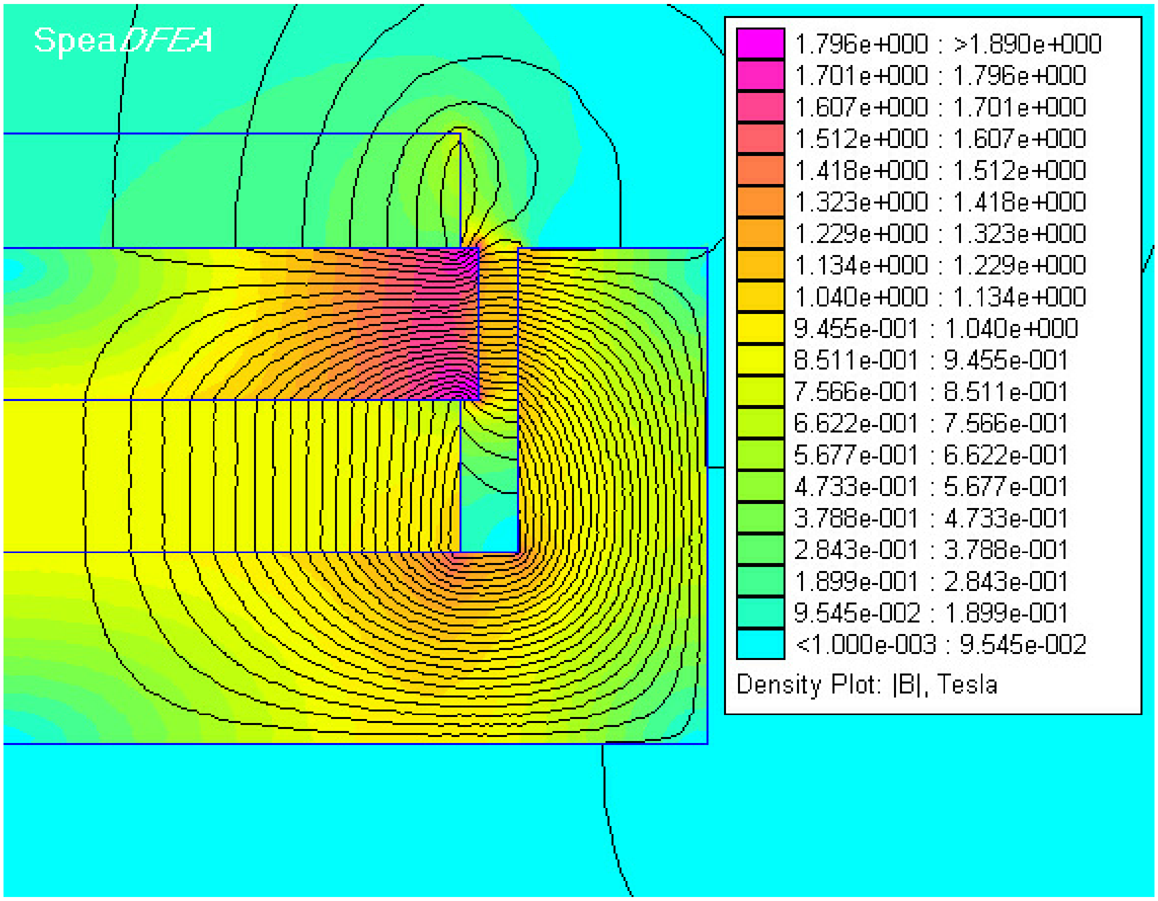
We know that we can increase the gap height to increase BL so let's see what happens when we increase the top plate to 4mm.

A 4mm thick magnet does not come close to bringing the top plate steel to the BH knee, so we have to increase the magnet thickness. Unfortunately, even doubling the magnet thickness to 8mm does not get us there.



What we need is increased magnet *area,* not increased magnet *volume*.

Now we come to one of the well-known tricks of motor design. Let's leave the 4mm thickness that we had on the first design and add another magnet in opposite polarity on top of the top plate. (This is sometimes called a bucking magnet.) The addition of a 3mm thick bucking magnet brings the top plate to its BH knee.



To achieve 2mm of Xmax, our coil height needs to be 8mm, so with the help of Spea*DFEA* we see that BL is 6.06 and coil Mmd is 1.46 grams. This gives us an efficiency ratio of 4.15. It's getting better.

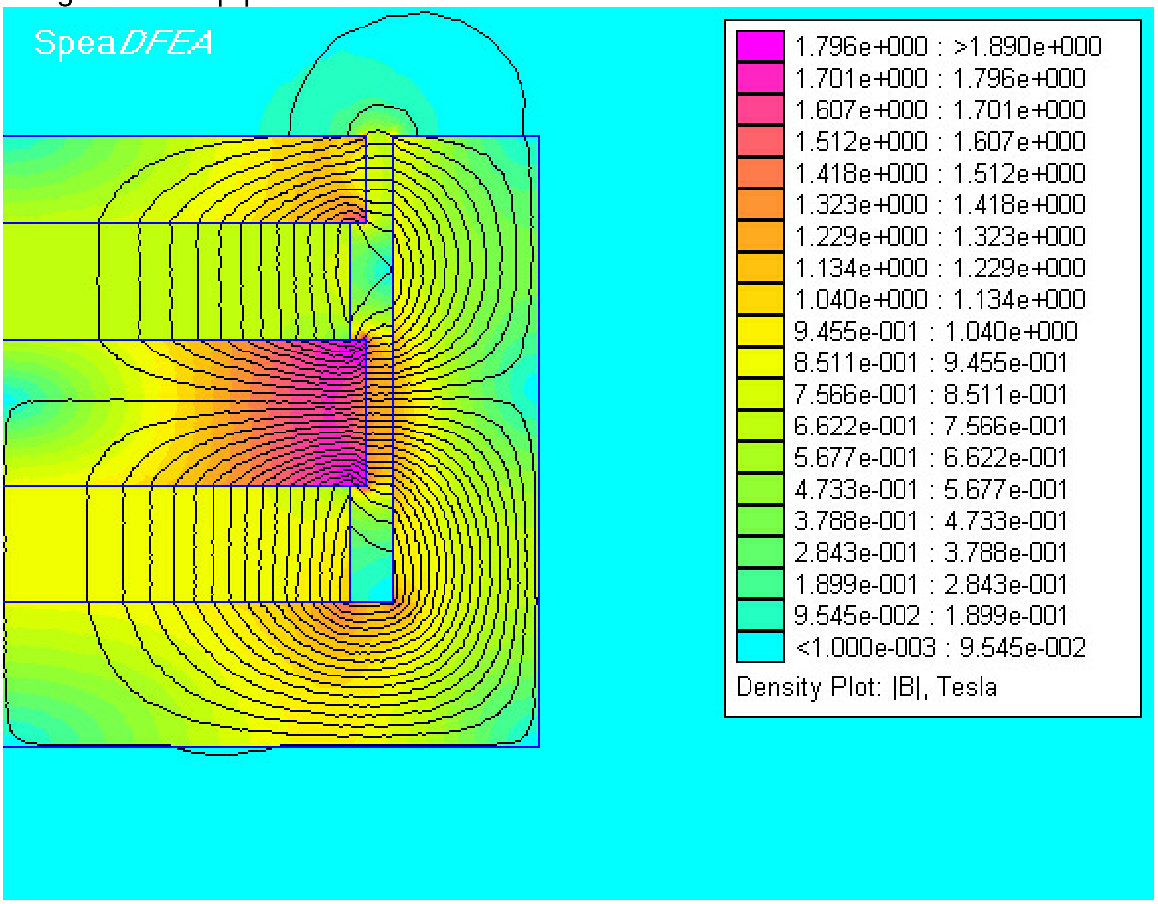
Design 3

Now let's see if increasing the top plate thickness again can give us an additional improvement. With a 5mm top plate we run into the same problem that we did before we added the bucking magnet in design 2 - increasing the primary magnet or bucking magnet thickness just doesn't get us any more strength.

So, for a 25mm neo motor an overhung efficiency ratio of about 4.15 (using a bucking neo motor), is about the limit for these deign goals. Or is it…..?

I was discussing this limit with my friend Enrique Stiles, bemoaning all the wasted potential strength in a bucking magnet. (If you look at the FEA plot, you can see there is barely any flux passing through the bucking magnet). In his casual way of seeing everything from a different perspective, he said "why don't we find a way use it?" He pointed out that by putting another plate on top of the bucking magnet and extending the yoke walls up to this new plate, we could provide a Low Reluctance Return Path (LRRP) for the bucking magnet. (Technically speaking, this changes the load line of the magnet which generates more magnetic flux). This additional flux would then be directed though the primary gap.

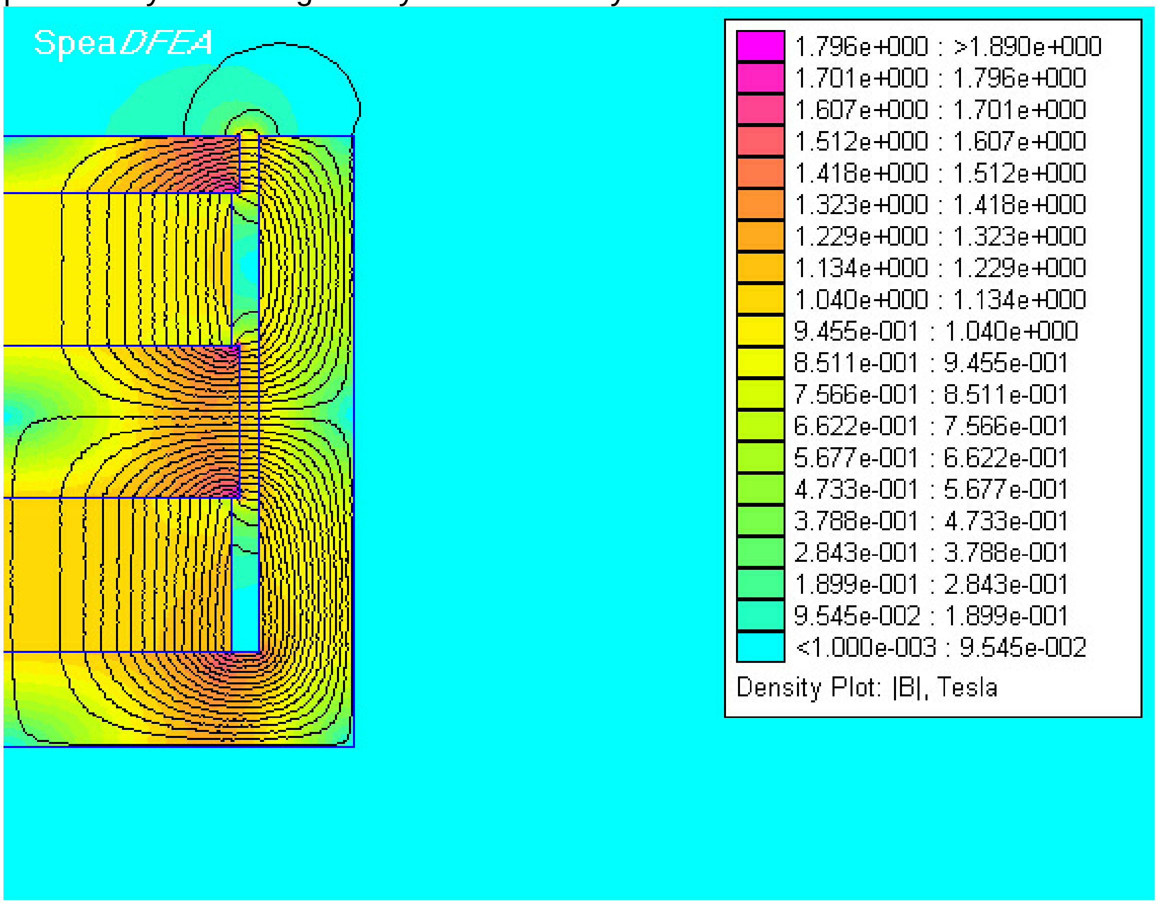
Using an LRRP motor, we can reach our design goals by using two 4mm magnets (one primary and one bucking and a 2mm low reluctance plate, and bring a 5mm top plate to its BH knee.



Using Spea*DFEA* we get a BL of 7.75 and a coil Mmd of 1.73 for an efficiency ratio of 4.47.
It is important to note that we are oversimplifying these comparisons. The thicker top plates will actually produce more functional Xmax including fringing, than the thinner plates produce. When this is included, the efficiency factor will be even greater.

Design 4

LRRP motors have an even bigger advantage when they are used to create underhung designs. Using an 8mm top plate and 4mm coil we achieve the target of 2mm Xmax. Driving the top plate to its knee requires 8mm primary and bucking magnets and a 4mm thick return plate. This design gives a BL of 5.1 and coil mass of .68, for an efficiency ratio of 7.5. For our design goals this will produce by far the highest system efficiency.



Retrofitting existing designs
It is also easy to retrofit existing designs to take advantage of a LRRP motor. For example, a well known 4” speaker using an underhung neo design with a 25mm diameter coil and 2.5mm of Xmax, uses a 10mm plate and 5mm coil. This design has a BL of 3.91. The simple addition of a Low Reluctance Return Plate and extending the yoke walls increases the BL to 4.74! That is an increase of 21% for a few pennies of extra steel (and a small license fee to STEP).

Braking Effect
Another interesting side benefit of the LRRP motors is that the additional bucking gap is in magnetic opposition to the primary gap. This means that as the voice coil approaches the bucking gap it is repelled. With careful design this can be used as a braking effect to magnetically limit the excursion of the speaker.

The STEP patent features many more useful applications for LRRP motors including using them in combination with Multiple Magnet Air Gap (MMAG) technology for very high efficiency - high excursion motors. (The 75mm speaker below has 6.5mm of linear Xmax!)

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Part Two
MMAG + LRRP = High Sensitivity and High Excursion

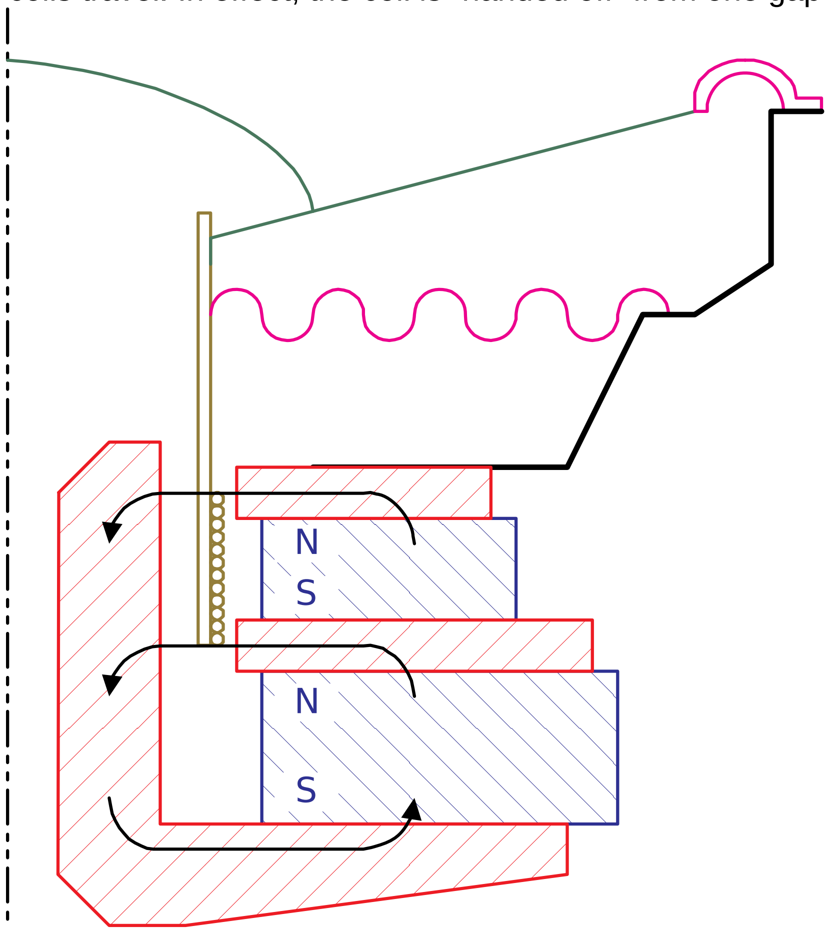
In part one you were introduced to Low Reluctance Return Path (LRRP) motors and how they could dramatically increase the gap B for internal neo motors. Like conventional speaker motors, LRRP motors still have to fall into either the underhung or overhung categories. (In part one we also saw that using LRRP with an underhung topology could offer significant advantages compared to overhung.)

Neither of these topologies offers optimum performance – especially when your performance targets include relatively high Xmax.

- For underhung motors you are driving 100% of the coil mass, however there is a limit to how much gap B can generated for a given coil size (at least with internal neo motors)
- For over hung motors it is easy to generate very high gap B, however you are never driving the entire coil mass.

In fact, ***for every coil diameter, there is an optimum balance of coil height to plate thickness for maximum sensitivity and Xmax****.* Many times, this optimum balance can not be achieved within the dimensional restrictions of the magnet system.

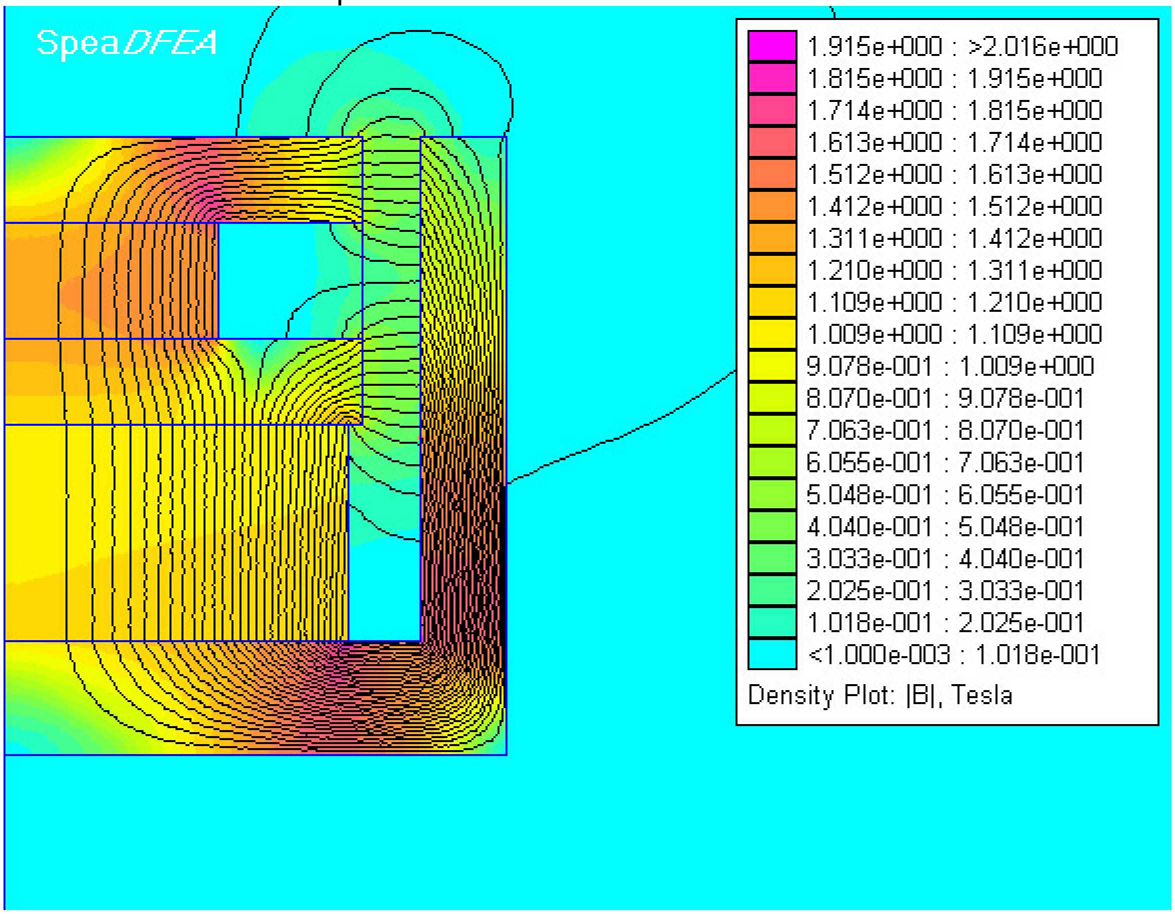
The solution to this is using a Multiple Magnetic Air Gap (MMAG) motor detailed in a handful of patents awarded to STEP Technologies. MMAG suspends a coil equally between two or more magnetic gaps so that the BL remains constant through the coils travel. In effect, the coil is “handed off” from one gap to another.



This provides two distinct advantages over conventional motor topologies. The first is that a much wider range of optimum coil height to plate thickness ratios can be achieved. (Think higher sensitivity *and higher Xmax*). The second is that the permeance coefficient of the motor can be optimized for a particular magnet material. (This means the most economical use of the magnet). For neo magnets this means a far more economical use of increases in magnet thickness.

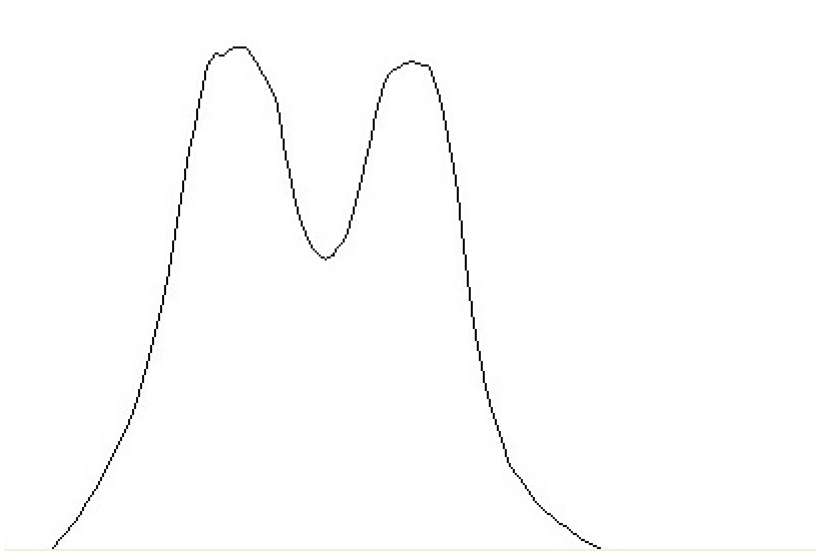
For every coil diameter there is a turning point in Xmax where an MMAG motor will yield higher sensitivity. The sensitivity advantage increases as you increase the Xmax past this point.

It is certainly possible to create a simple MMAG design with an internal neo motor. Here is an example:

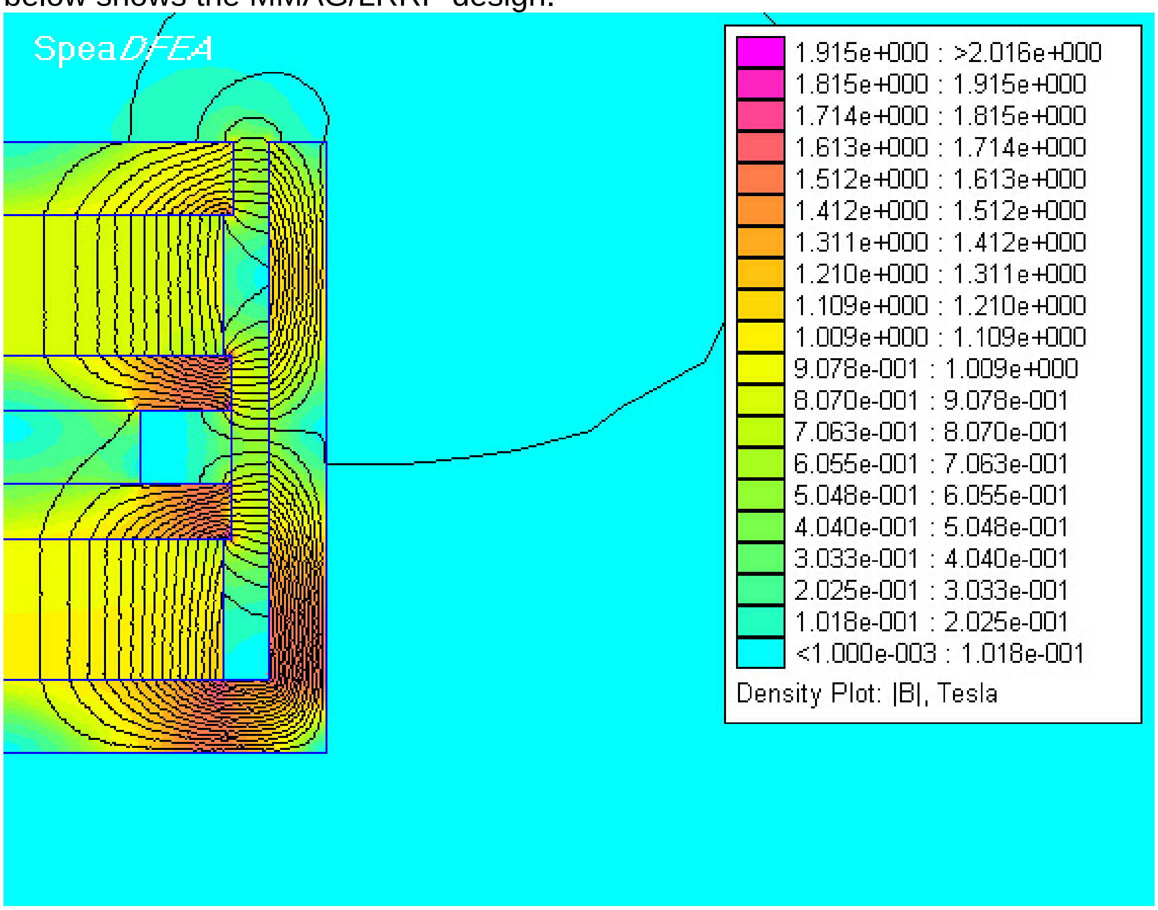


Note that there is an aluminum ring between the two gaps. This is another big advantage of MMAG; you can place a shorting ring right next to the voice coil – more about this in part 3.

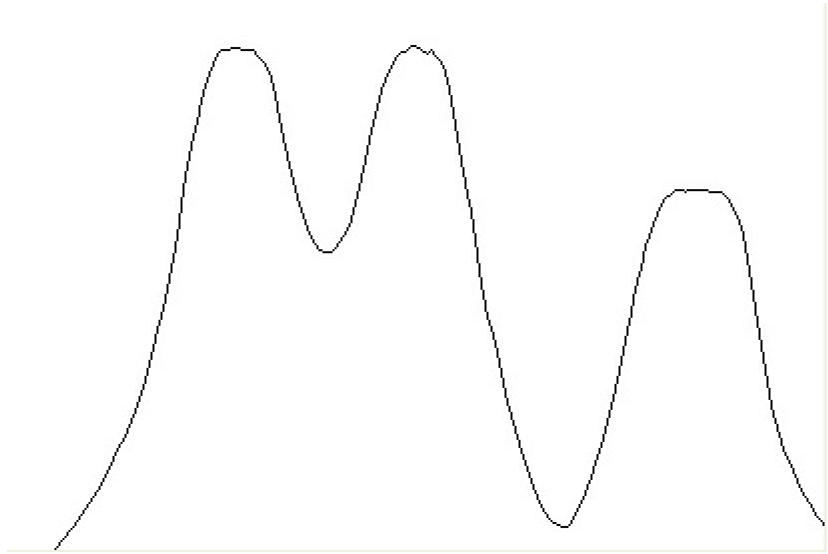
The graph below shows the B curve through the center of the gap. The top gap B is .46 T and the bottom gap is .4 T. Ideally these are identical, and a with a bit more FEA work this can easily be done. The total B integrated across the 7.3mm coil is. .4 T. If you multiply this number by the length of coil wire in meters you get BL in Tesla/meters.



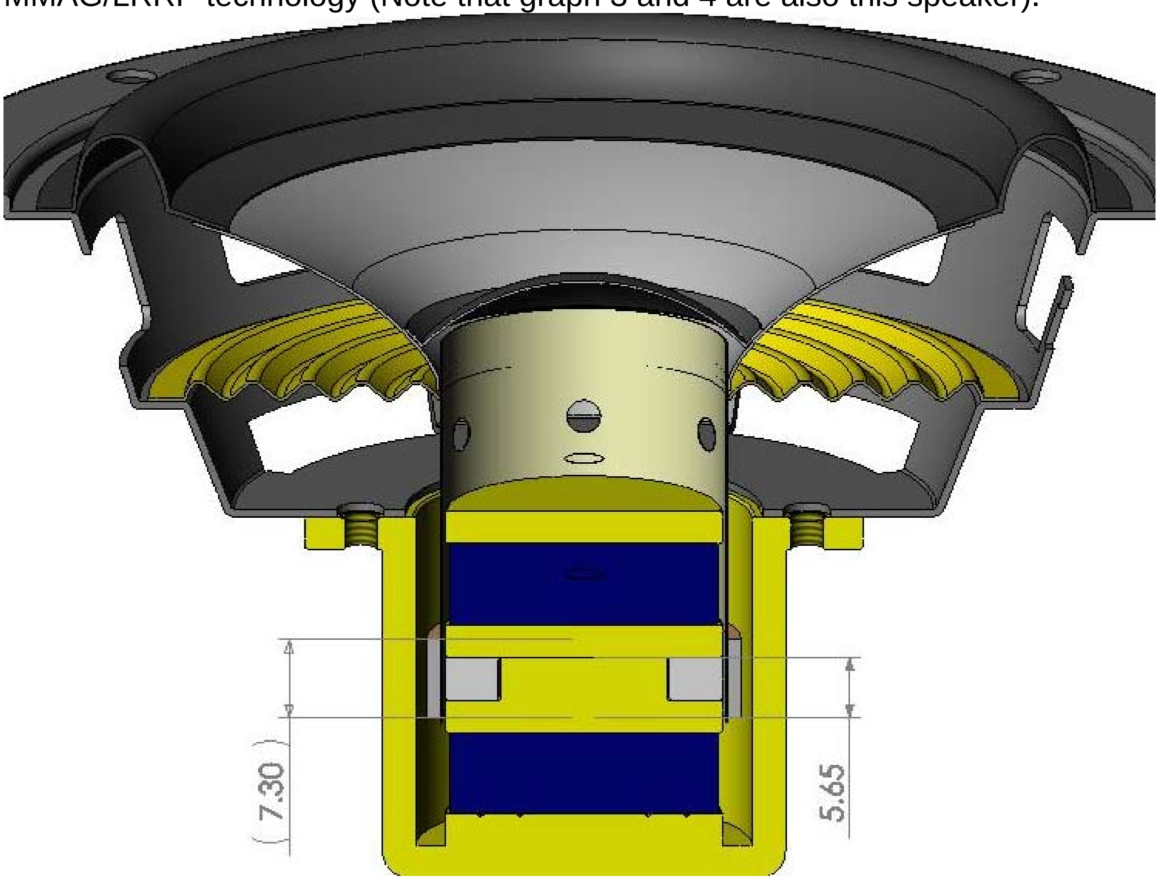
As we saw in part 1, it is possible to use a bucking magnet and LRRP to increase the gap B dramatically. With an MMAG design it is even more effective because the two gaps produce a more efficient point on the magnet load lines. The plot below shows the MMAG/LRRP design.



The Graph below shows the B curve including the LRRP gap. Both the upper and lower gap B's are .78 T. So the gaps will act symmetrically. The integrated B across the same 7.3mm coil is now .71 T for a 73% increase in B!

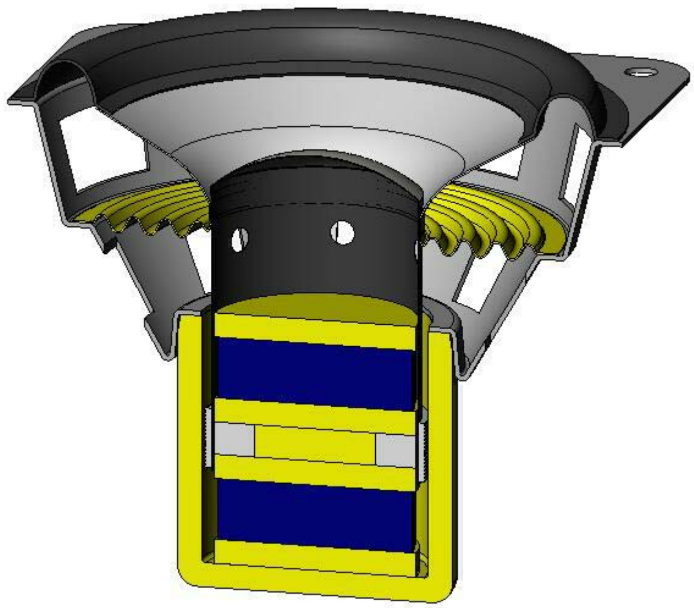


The picture below shows a cross-section view of a real speaker using the MMAG/LRRP technology (Note that graph 3 and 4 are also this speaker).



The physical Xmax for an MMAG motor is calculated by: (WH-Gapspace) / 2 + Gap. For this speaker the gapspace is 4mm and we know the coil is 7.3mm so the physical Xmax is 5.65mm. Assuming the functional BL is defined as a reduction of 10% then the linear Xmax for this speaker is about 6.5mm.

In part 3 we will test a sample of this speaker on Klippel to verify its performance and discuss some of the additional benefits of this motor design.



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Part Three, The Final Product!

Part 2 described the advantages of using the combination of Low Reluctance Return Path (LRRP) and Multiple Magnetic Air Gap (MMAG) technologies. The motor described in the last article is used on a new product built by Magnetic Technologies Inc. (www.mtispeakers.com) The performance matches the predictions exactly and produces a speaker that raises the bar for high excursion midbasses.

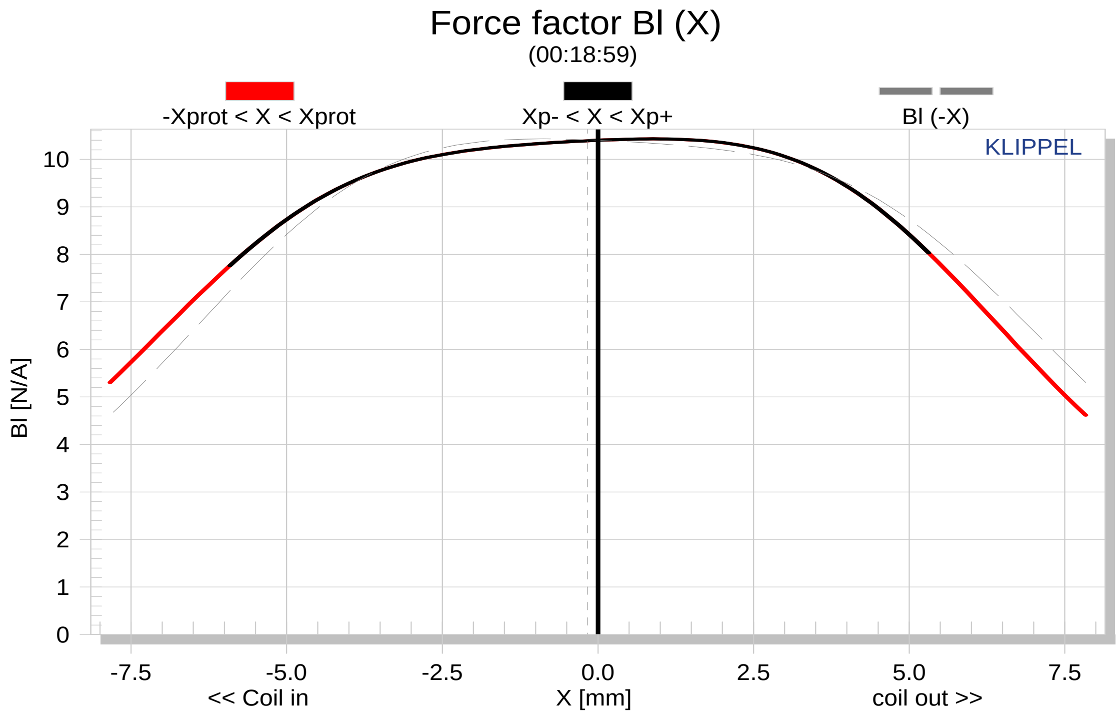
The MTI 4LRMMAG, is a 100mm, (4") midbass. It features very high excursion, high sensitivity, low distortion speaker with excellent frequency response extension. With roughly twice the linear Xmax of its closest competitor and similar or higher sensitivity, it can dramatically improve the maximum output for existing products – or create new product categories that were previously impossible. Bold statements, but lets look at the test data:

The sample tested was designed for line array use so the Re is fairly high at 19 ohms. There are 2 other models available at lower impedances which are summarized in the chart below

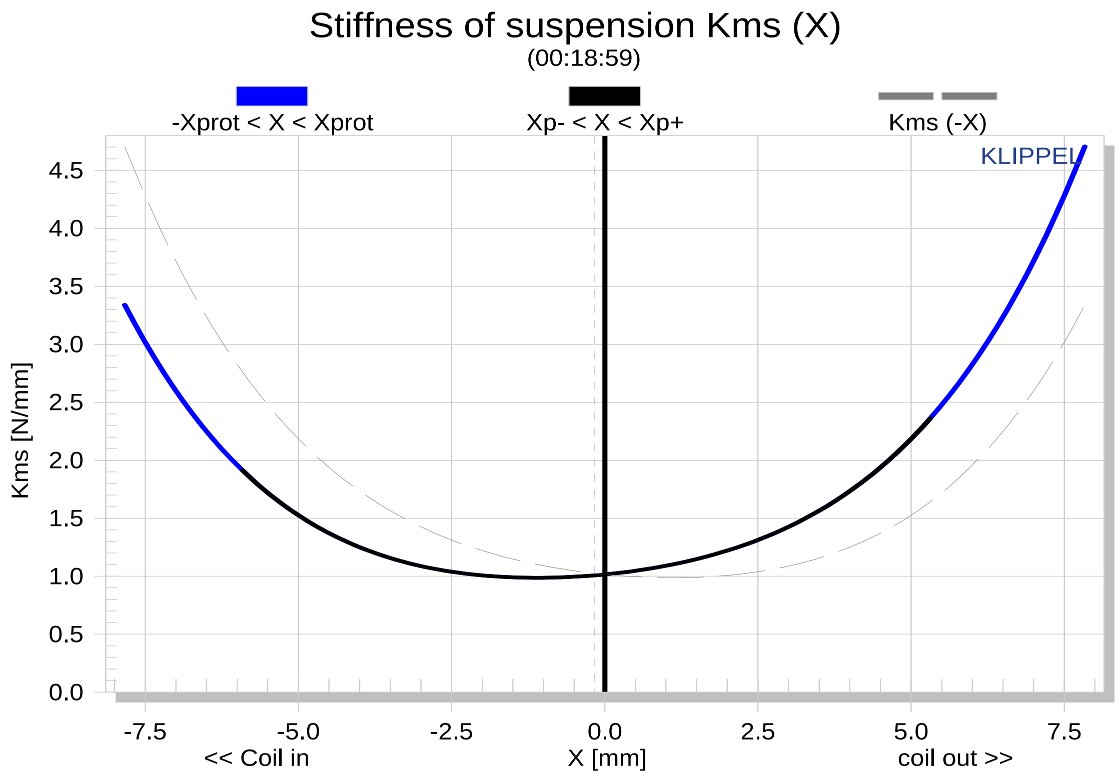
		4LRMMAG 19	4LRMMAG 6	4LRMMAG 19
Sd	Cm^2	54.76	54.76	54.76
Re	Ohm	19	6.2	3.99
Fs	Hz.	72.9	71.87	70.65
Qms		2.62	2.57	2.4
Qes		.58	.44	.419
Qts		.48	.376	.357
Vas	L	2.79	2.69	2.69
Bl	Nm	10.4	6.99	5.79
Mms	gram	7.23	7.67	7.94
SPL 1W/1m	dB	84.75	85.48	85.47
SPL 2.83V	dB	80.98	86.59	88.49

The nonlinear parameters from Klippel distortion analyzer testing show (similar for all of the models):
XBl: 6.0mm
Xc: 5.9mm
XL >6.0mm

These numbers are quite close to the predictions we made last month of between 5,7 and 6.5mm of XBl.
The following graphs show the Klippel nonlinear data:

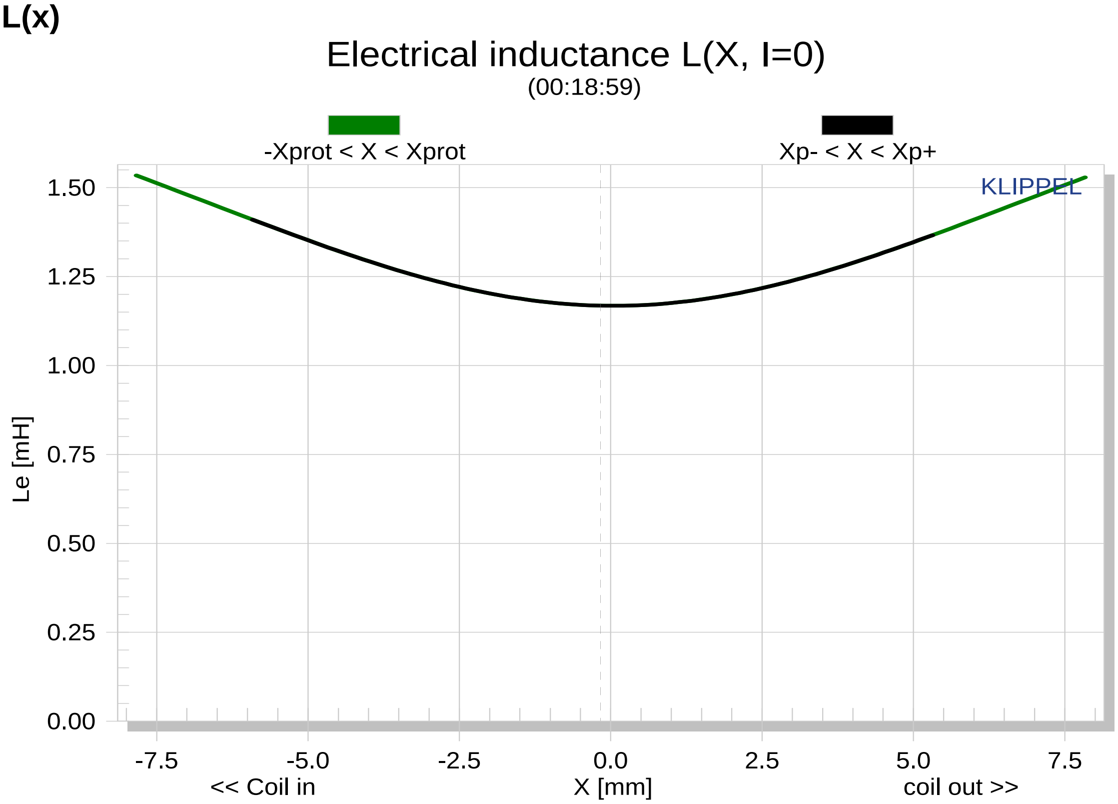


Note the symmetry is nearly perfect. This is a good example of balancing the gaps in an MMAG motor (which is actually quite easy).



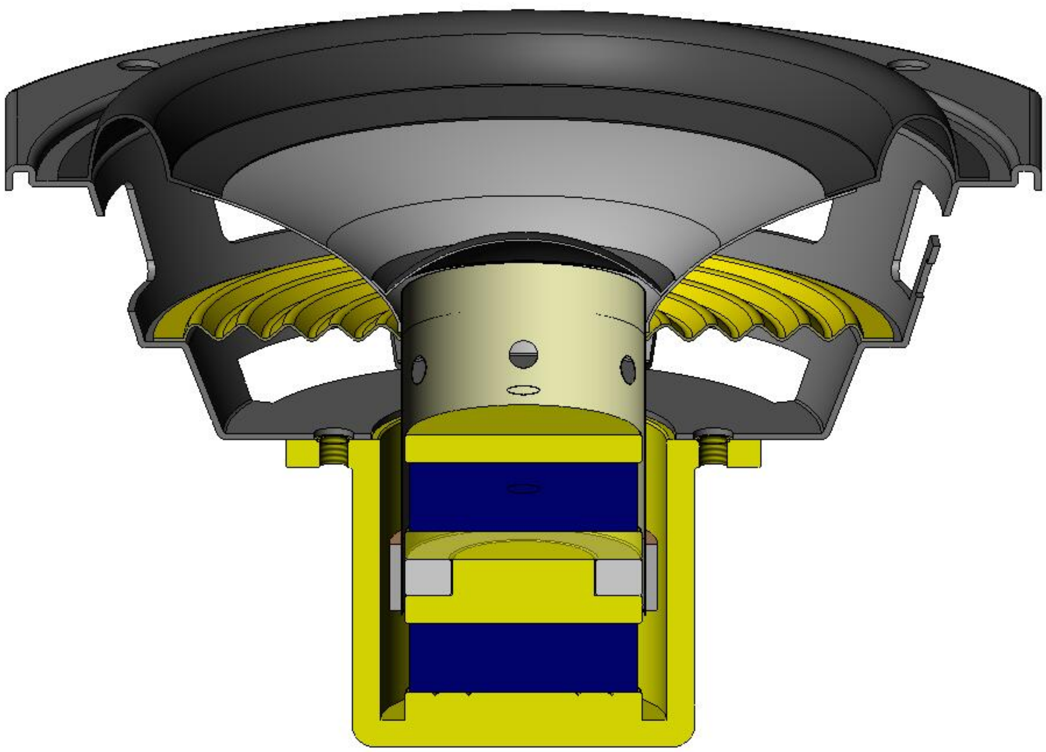
The Kms(x) symmetry is not quite a perfect in this sample however a spider geometry change will imrpove this in production units. Still, the total asymmetry on this sample is only 1.5mm.

L(x)



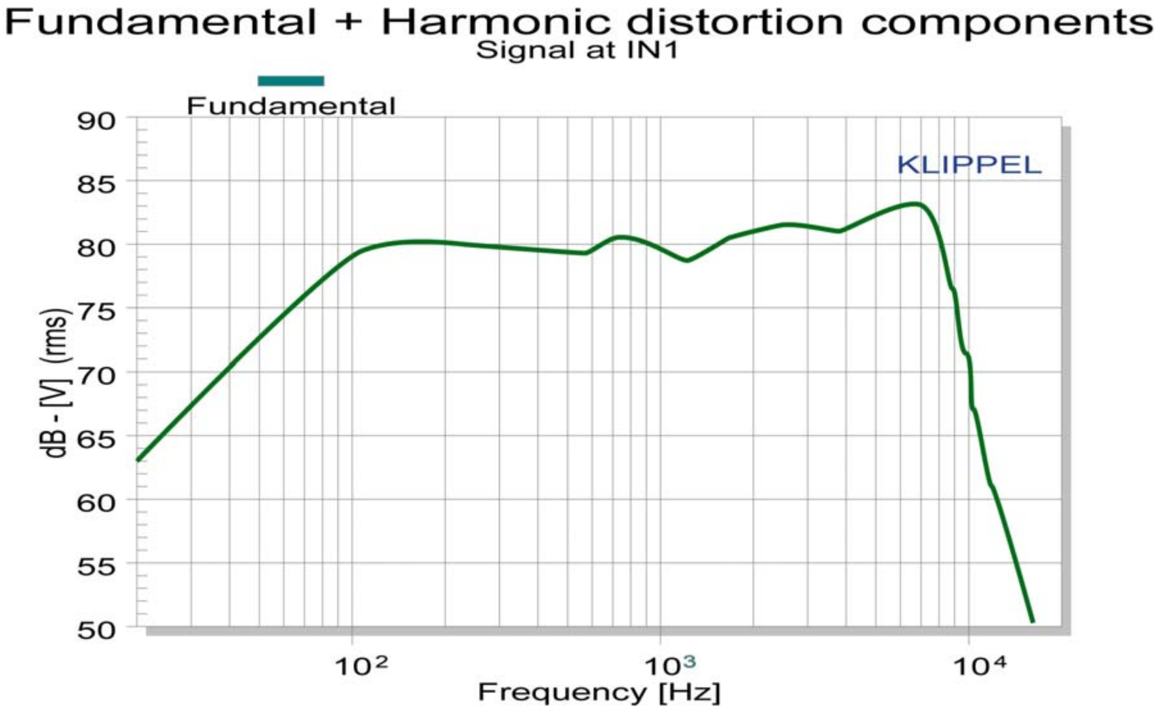
The non-linear inductance created by this motor system is virtually unique in speaker designs. Putting a shorting ring in the center of the virtual gap creates almost perfect symmetry, very low inductance and very low eddy currents in the steel parts. Klippel has shown that non-linear inductance is the most objectionable of the three non-linear components. The LRRP/MMAG motor reduces this component below the audible range even at maximum excursion.

If you didn't notice the ring in the last article, here is another cross-section view showing its placement. (note the top plate of the MMAG Gap is made transparent to help see the
ring)



The frequency response of the speaker is also quite good with very little edge hole problems considering the tall roll necessary for the high excursion. This was achieved by a combination of non-linear mechanical FEA to create good symmetry in both directions and the use of FineCone to optimize the cone, edge and cap shapes for a smooth frequency response.
Note the extended high frequency response – out to 7 kHz!. This is virtually impossible with any other motor system. It is another product of the short coil and low inductance of the MMAG motor.

This response is the 19 ohm version with 2.83 volts input. The 1W / 1m sensitivity is actually 84.75. For the 6 and 4 Ohm versions, the sensitivity is 85.5.



The final advantage of the MMAG/LRRP motor is the thermal mass directly next to the voice coil. For the majority of the coil's travel it is adjacent to steel or aluminum. These materials help keep the coil cool at high power levels. The Heating Coefficent or R_{th} of the speaker is 5.66. Which means for each watt of power (nominal) the coil temperature rise 5.66 degrees C. Note this number is calculated when the second time constant has leveled. The coil has a maximum temperature of 220 C so the continuous RMS power handling is 35 watts. This could be improved with the addition of a heat sink on the rear of the Cyoke.