4.8 Field Distribution in Materials

There is a simple relationship between flux density and field strength in vacuum (or air): $B = \mu_0 H$. In ferromagnetic materials things are much more complicated; here, μ is much bigger than μ_0 and depends non-linearly on H. A larger permeability μ means a higher magnetic conductivity, hence a smaller magnetic resistance. If one assumes that **field lines** (flux lines) always "seek" the path of smallest resistance, one gets a descriptive explanation for the effect of ferromagnetic materials within a field: they "suck," so to speak, nearby field lines into themselves and, thus, encounter – despite the somewhat longer path – a smaller overall resistance. The specialist literature offers yet more comprehensive models, in which e.g. microscopically circular currents are anticipated as the origin of any kind of magnetic behavior. However, for simple cases basic models are completely sufficient.

The simplifying differentiation into magnetic and non-magnetic materials is very convenient for the description of the magnetic behavior of common guitar pickups, because para- and diamagnetism do not play a role. Air, wood, plastics, lacquers, brass, copper, aluminum, German silver (nickel silver) (and many more) are, thus, non-magnetic. Steel♣, nickel and iron are (ferro) magnetic. A copper plate cannot, as some suspect for the Telecaster pickup, "reflect the magnetic field" because, for stationary fields, there is no difference between air and copper. In fact, there is no copper plate underneath the Tele-pickup but rather a *copper-plated* steel plate, which was also sometimes tin-plated, zinc-plated or something else – that is a different story. Ignoring the thin copper layer and assuming a ferromagnetic behavior for the rest means that we have a magnetic material located in the field of one (or several) permanent magnets. How does this change the field profile and what is the effect of this material?

Ferromagnetics conduct magnetic fluxes better than air, comparable with a drainage pipe in the soil that should drain its vicinity: "Mühsam sind des Wassers Wege, in der Erde fließt es träge, doch in Rohren aus Schamott, rauscht's von hinnen mächtig flott♦." Drainage pipes have a lower flow resistance than soil, and this is similar for magnetic fields: The flux density is increased inside the ferromagnetic material and is decreased in the neighboring air. In **Fig 4.28** the field-focusing effect of a ferromagnetic material is depicted for three different permeability values (= conductivities): the higher μ is, the larger is the effect. However, it is not unlimited: even for a very high magnetic conductivity, the effect on the outermost field lines is marginal – they are already too far away.

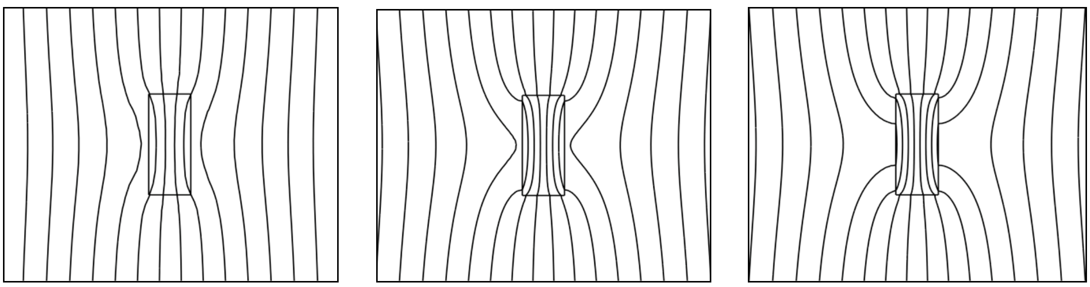

Fig. 4.28: Field line patterns in ferromagnetic materials for stationary parallel plane magnetic fields with no eddy currents. For simplification, the permeability is chosen as locally constant: μ = 5, 50, 5e6 (left to right).

♣ Some steel grades are non-magnetic ♦German rhyme (no, not by Schiller) – very roughly translated: "Arduous is the water's path, in the earth it runs sluggishly, but in pipes made of clay, it very quickly runs away."

The efficiency of the field enhancement (or flux enhancement) of the ferromagnetic material is described by the **permeability** μ (chapter 4.3). There are already clear differences between $\mu = 1$ (e.g. air) and $\mu = 5$ (Fig. 4.28), also between $\mu = 5$ and $\mu = 50$. However, with increasing μ the visible gain becomes smaller and, even with $\mu = \infty$ (compared to $\mu = 50$), there is no further dramatic change. **Fig 4.29** illustrates this with an example: As long as there remain magnetic resistances (air-gaps) in front of or behind the ferromagnetic material, field lines escape into the air space.

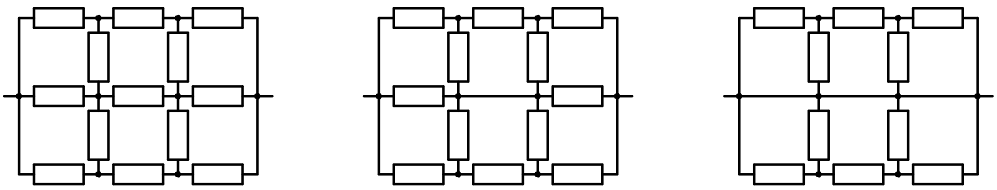

Fig. 4.29: Electrical current flow through a locally discrete model. A current still flows in the outer branches even when the central resistance is decreased to zero, (middle picture). The outer branches are only free of current flow for a complete short circuit (right picture). Analogy: electrical current ↔ magnetic flux.

The above assumed limiting case $\mu = \infty$ in fact is not achievable, but it is helpful for boundary layer considerations: under this limiting case the field strength within the metal turns to zero, because B cannot become infinite. From the continuity condition of the boundary-parallel tangential field strength it can be deduced that the air field strength along the metal boundary also has to be zero. According to $B = \mu \cdot H$ the flux density in air also has to be zero. The immediate vicinity of the (lateral) boundary layer is, therefore, approximately magnetic field free. The quantitative value of the flux density, e.g. in Fig 4.28, can be visualized by the distance between neighboring **field lines**: The denser they run, the larger is B. Since it was assumed that air is the medium around the ferromagnetic material in Fig. 4.28, regions of high flux density (above and below the square) are also regions of high field strength. Accordingly, beside the square, there are regions of relatively low flux density and field strength. It is arbitrary which figurative density of field lines (lines per centimeter) one associates with a particular value of the flux density and it is dependent on the line width, the print quality and angle resolution of average eyes. With only 1 line per cm one may give away space, with 100 lines per cm one may overburden printer and observer. Scaling hints in the picture (e.g.10 lines/cm $\hat{=}$ 1 T) may be helpful, but were left out in the figures because only the relationships are of interest here. If one splits the field vectors at a **material interface layer** (wall) into a wall-parallel (tangential) and a wall-normal component, it follows:

The wall-parallel field strength as well as the wall-normal flux density is always steady. If the permeability on the one side and the other is different the wall-normal field strength and the wall-parallel flux density are unsteady.

For the general case, i.e. for varying permeability, every field line will form a kink at the material interface layer – it is broken, like a ray of light. The larger the difference of both permeability values, the larger the kink. For the angle (α) to the normal of the interface and the tangential flux density B_t this yields:

$$\mu_2 \cdot \tan\alpha_1 = \mu_1 \cdot \tan\alpha_2 \qquad \mu_2 \cdot B_{t1} = \mu_1 \cdot B_{t2}$$ Interface conditions [7]

Generally, the permeability of ferromagnetic materials is large and so the field lines will exit approximately vertical from them, i.e. normal to the wall.

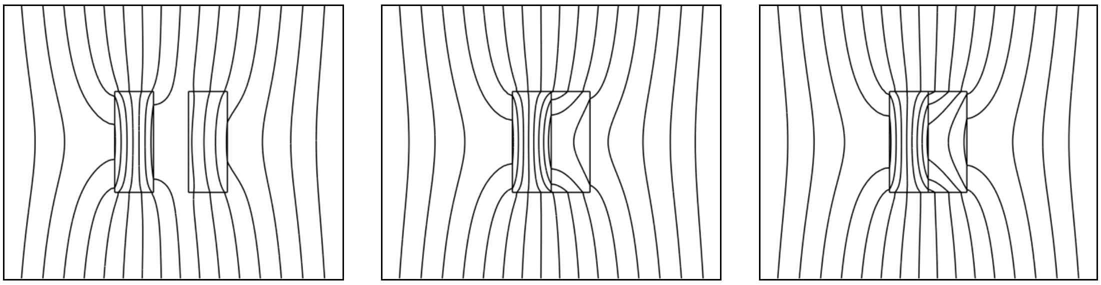

Fig. 4.30: Parallel magnetic conductors; $\mu = 500 / 5$ (left), $\mu = 500 / 5$ (middle), $\mu = 500 / 50$ (right).

Fig. 4.30 shows how two magnetic conductors influence each other. If positioned parallel in the flux direction, each conductor bends the course of the flux density not only in the surrounding air, but also in the neighboring magnetic conductor. The material of higher magnetic conduction (left in the picture) diminishes the magnetic flux in the material with lower conduction and, thus, forms a sort of shielding. The magnetic conductors act on each other as flux enhancing when positioned in series with respect to the flux (**Fig 4.31**): the magnetic conductor placed in front of the other seems to concentrate the magnetic lines like a "convergent lens".

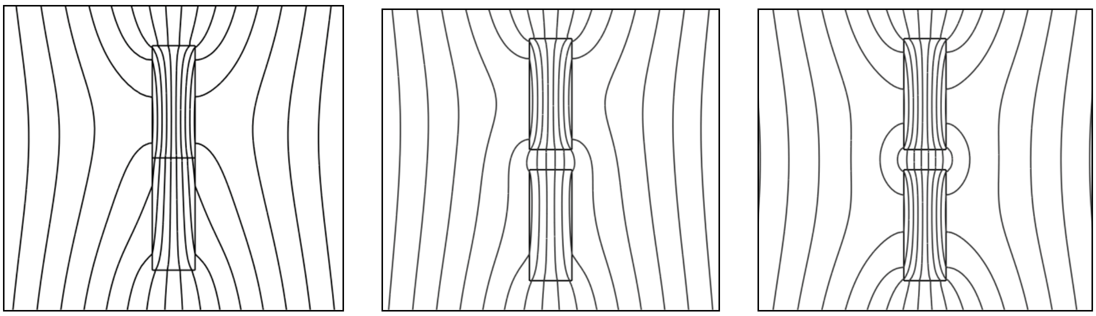

Fig. 4.31: Serial magnetic conductors; $\mu_{above} = 500$, $\mu_{below} = 5, 5, 5e6$ (left to right).

If two materials with good magnetic conduction are placed together, one has to pay attention to the **air gap** in between them, especially in serial configurations: because of the possibly large differences in permeability, very small gaps may lead to considerable magnetic resistances. For pot cores, air gap clearances of e.g. 0.1 mm have to be met with a precision of only a few µm.

A constant **permeability** was used for the calculations of Figs. 4.28 and 4.31, which may be permitted for introductive treatments. However, accurate analysis will need precise material parameters and, consequently, the calculation effort will increase. In fact, there is a mutual dependency between flux distribution and conductivity: high conductivity will yield high flux density but this will also (as a function of the declining hysteresis curve) lead to a decreasing conductivity. This will yield a lower flux density and in turn a lower conductivity – it is a very complicated coupled system.

Non-linear FEM-models approximate this iteration process by many (sometimes even very many) calculation steps, which may occupy a PC for half an hour, or maybe even longer, according to the complexity of the task and the performance of the computer. In addition, not every material is magnetically isotropic. In fact, for a single crystal, magnetic **anisotropy** is the rule and not the exception. If a magnetic field is applied pointing in one of the preferred directions, the magnetization energy is lower than for the other directions. Homogenous spatial distribution of the magnetic crystallite orientation may lead to isotropic (non-directional) macroscopic behavior, but the crystallite orientations are not always uniformly distributed. In fact, for grain-oriented Alnico-5 magnets a special **anisotropy** is perfected, at pole pieces and/or strings it can happen more or less accidentally as a side-effect. Fig. 4.30 has already shown that field lines in a material may run in very different directions. For anisotropic substances the material parameter tensors would have to be specified for FEM calculations, and they are often not available with sufficient precision.

As long as a parallel-plane field is assumed, like in Fig. 4.28 to 4.31, the computational effort can be limited, to some extent, because one can calculate with plane mesh elements. Rotational symmetry may also reduce the calculation effort but, for general 3-D models, things become elaborate. Yet, this is exactly what is necessary for the computation of the magnetic field of a pickup. All these challenges, such as non-linearities, inhomogeneities and anisotropies, impede the calculation, but they do not prevent it entirely: The stationary flux can be determined with sufficient precision. However, the real challenge is yet to come: the magnetic flux which is important for the induction voltage is the alternating flux, i.e. the time-dependent change of the steady flux. This part of the flux is only about 1% of the steady flux! An FEM calculation with "only" 2% accuracy will suddenly lose its original attraction.

On the other hand, if only the basic magnetic flux characteristics need to be described, e.g. for qualitative considerations, FEM calculations are mostly helpful tools. In **Fig. 4.32** a U-shaped metal bar within a magnetic field is shown. A similar arrangement can be found for Humbucker pickups (Chapter 5.2, 5.7), with a central bar magnet and adjacent pole pieces. The left picture immediately shows that the humbucking effect might not be sufficient – even though the magnetic flux representation may quantitatively not be drawn with particular precision.

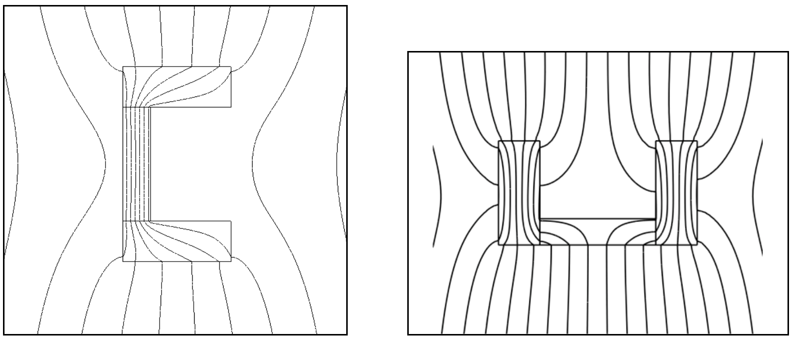

Fig. 4.32: U-shaped bar.

It is hardly possible to represent the magnetic fluxes of a guitar pickup with sufficient precision. The calculation is very elaborate, because one has to deal with non-linear, inhomogeneous, time-dependent and unsymmetrical fields. Further, measurements are difficult, because the lateral dimensions are so small: the diameter of the treble strings is only a few tenths of a millimeter. So, one would need very small Hall-generators which are moved by micro-manipulators on defined paths to determine the spatial extension of the fields. The measurements presented in chapter 5 are, presumably, the first of their kind, but surely not the most precise ones. This makes a basic insight possible, but the differences between similar pickups cannot be deduced from this data yet – to improve, one would need measurement tools which are beyond the current college budget.