

5. Magnetic Pickups

In a magnetic pickup (TA) the vibrating string produces an alternating magnetic field which generates a voltage in a wire winding (coil). The string in itself in its original state is not magnetized; the magnetization is derived from a permanent magnet installed at a small distance under the string. Consequently, the pickup consists of a permanent magnet and a coil plus some housing components, which keep everything in place. Sometimes additional metal parts are included to guide the magnetic field.

The magnetic pickup belongs in the category of passive magnetic transducers [3] and uses the electromagnetic conversion principle. The vibrating string changes the magnetic reluctance resistance in the permanent magnetic circuit, and due to temporary magnetic flux changes in the coil an electric voltage is induced. The magneto-electric conversion must not be confused with the electro-dynamic conversion – in the latter a voltage is induced in an electric conductor moving in a magnetic field. Examples for electro-dynamic transducers are the dynamic loudspeaker and the dynamic microphone. For both it is the coil which moves relative to the magnet. In a guitar pickup coil and magnet are fixed relative to each other. Although a minute induction voltage is generated in the moving steel string this effect is not exploited.

5.1 Single-coil pickups

Close to the bridge, the six strings of the guitar have a distance relative to each other about 1 cm. In order to generate the loudest possible signal, every string has to be subjected to a strong magnetic field. For many pickups, this is achieved by the use of six cylindrical permanent magnets positioned in parallel and having a diameter of about 5 mm and a length of about 1 cm. They are oriented all in the same way i.e. such that all north poles point in the same direction. The magnets are stuck in a **bobbin for the coil wire**. The coil is protected against damage by insulating tape or by a proper housing. Two to four screws keep the pickup at a short distance below the strings. Most electric guitars have two or three pickups; one or four pickups are more rare. A special design form is the twin-coil humbucking pickup. For these pickups two coils are positioned side by side in the same housing. This design reduces the sensitivity against external noise.

Instead of the six individual magnets, alternatively a **bar magnet** positioned below the coil may also be used. For improved field guidance six cylindrical iron slugs are inserted through the coil in this case. On their lower side, these slugs (also called pole-pieces) touch the magnet, or they are held in a metal bar which touches the magnet. Often these pole-pieces are designed as screws such that the volume of each string can individually be adjusted. Over time, different pickup designs came into existence – the most important ones are being compiled at the end of the chapter

To shield the pickup against **electrostatic interference**, metal covers are sometimes installed over the pickup coil. In practice, the **effect of this shield** is rather modest because the main interferences are not due to electrostatic but due to magnetic interference fields (such as they are e.g. generated by transformers). Against magnetic fields a pickup should not be shielded due to its working principle. The string vibrations are generating also a magnetic field and it is this field which the pickup needs to sense - a cover made out of magnetic material consequently is ruled out. Moreover, even shielding covers made of un-magnetic material (e.g. brass or nickel silver) can have undesirable effects on the magnetic field because **eddy currents** are generated within the material which themselves again generate magnetic fields. Many guitar players therefore remove the pickup covers and achieve a small change in sound: the pickup resonance emerges a bit more strongly which usually which often is perceived as sounding better

The magnetic guitar pickup has a long history. In 1831, the English physicist MICHAEL FARADAY (1791 – 1867) made the fundamental discovery that an electric current is flowing in a closed conductor loop penetrated by a magnetic field of changing strength. At the same time – but independently – the American physicist JOSEPH HENRY (1797 – 1878) arrived at similar conclusions. The quantitative correspondences between the changing magnetic flux density and the voltage induced by it are described by the **induction law** (see chapter 4.10) which is called the FARADAY-HENRY-law after their discoverers. About 100 years after its discovery this law yielded the basis for the mechano-electric transduction of the sounds of the guitar which up to that time were rather soft in nature: the electromagnetic pickup emerged. Who in fact built the very first magnetic guitar pickup cannot be established with absolute certainty. DeArmond, Rowe and Beauchamp are often mentioned, and likewise manufacturers such as Rickenbacker, Gibson, Epiphone, Gretsch. National – and Fender, of course.

Leo Fender facilitated the commercial breakthrough of the solid-body guitar. Teaming up with George Fullerton, he developed the prototype for an electric guitar of solid wood in 1949. This instrument was introduced to the market in spring of 1950 under the name **Esquire**. In autumn of 1950, the 2-pickup **Broadcaster** followed, being renamed **Telecaster** shortly thereafter. Leo Fender's original guitar is seen as the archetype of all solid guitars, even though Lester Polfuss, better known under his pseudonym **Les Paul**, had already been working on a similar concept for more than 10 years. However, his ideas – picked up by Gibson – made it into production only by 1952.

The first Fender guitars were fitted with simple single-coil pickups - a tradition which is retained to this day. Leo Fender used an individual cylindrical magnet for each string, according to his own words this was to minimize the interaction between neighboring strings. Together with flanges pressed on to them, the 6 magnets form the coil carrier (bobbin) around which very thin enameled copper wire is wound. The magnet diameter is 3/16" (approx. 4,8 mm); the length of the magnet varied over the years (and across various Fender guitar models) from 12 to 19 mm. The magnets consist almost exclusively from Alnico-5 (also known as Alnico-V) which is a magnetic alloy developed in the 1940's. The flanges were first made of vulcanized fiber of approx. 2mm thickness; this is a high-strength, horn-like material. The color and thickness of the flanges varied over the years, and from 1980, injection-molded bobbins were also used. The diameter of the magnet wire wound around the 6 magnets is measured according to the American Wire Gauge: most pickup coils are wound with AWG #42 but in some cases the thinner AWD-#43 wire is used (see chapter 5.5.).

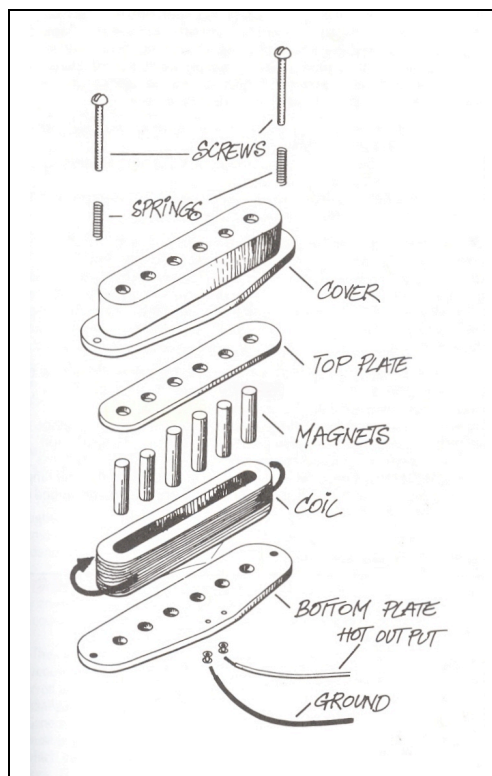


Fig. 5.1.1: Components of a Fender-Stratocaster-Pickup [Duchossoir].

Fig. 5.1.1 shows the components of a Fender single-coil pickup, in this case a Stratocaster pickup recognizable from the plastic cover. The characteristic feature is the group of 6 cylindrical magnets onto which the winding is directly placed. The two Telecaster pickups are structured in a similar way although there are some minor different details. Using the same basic construction principle, the Jazzmaster pickup was developed in 1957 - it however clearly departs from its predecessors in its dimensions. Leo Fender sought a different sound and widened the coil from 12 to 35 mm, while at the same time reducing the pickup length. *“The Jazzmaster pickup wasn’t so deep, and it was wider, thinner, more spaced out. See, the more spaced out the coil is – the wider the spectrum under the string – the warmer the tone. But a broad spectrum of tone places a lot bigger demand on the amp, and the earlier tube amps we had were kind of limited in the amount of power they could handle.”* [Wheeler].“

From the point of view of today's systems theory, Leo Fender's above explanation is not comprehensible. One could surmise that the thinking then was to sample a longer part of the string vibration via a wider coil, i.e. longer magnetic window (the magnetic aperture) was desired. However, as will be shown by the analysis in Chapter 5.4.4, the length of the aperture is in practice only dependent on the diameter of the magnet irrespective of the coil. Fender's referring to *spectrum* also remains unclear: surmising that he desired a larger window-length, one would expect a *narrower* bandwidth since time and frequency have a reciprocal relationship. Conversely, Leo Fender talks about a *wider* spectrum to which he attributes a *warmer* sound. Again, this does not fit: warmer sounds result from attenuating the treble, i.e. are connected to reduced bandwidth. Bandwidth reduction, however, cannot be what Fender meant, either, because his statement that a broadband signal challenges the amplifier more is correct. It seems wise not to expect a lot of theory behind the first pickups: the systems theory was still the new kid on the block in those days, and the development objectives were not governed by science but by an empirical approach and sales reports.

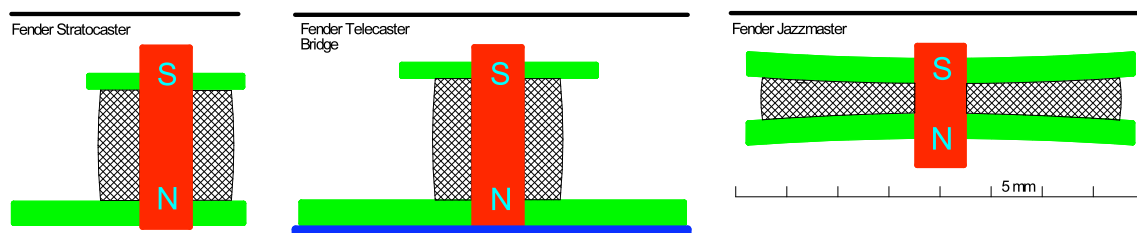


Fig. 5.1.2: Cross-sections of Fender pickups: Stratocaster, Telecaster (Bridge), Jazzmaster.

In **Fig. 5.1.2** shows cross-sections of Fender pickups. The heavy line at the upper border marks the position of the string while the cross-section of the coil is represented by the crosshatched area. Length and protrusion of the magnets changed several times for the Stratocaster and Telecaster – only the Jazzmaster-pickup with its relatively short lifespan retained its geometry.

The magnets of the first pickups were mounted flush with the upper flange (the one closer to the strings), but as early as approx. 1954 **staggered pole-pieces** were introduced i.e. the magnets were protruding unevenly from the upper flange. This allows for compensating for different loudness of the individual strings – but NOT by the musician! Recommendations to shift the magnets with light hammer strokes such that all strings have equal loudness may meet with a rather unexpected success. If in this process the coil wire directly sitting on the magnet is torn, indeed the loudness of all strings will be equal: it will be equally at 0! The philosophy behind the staggering is unclear: the first "staggered" pickups had the D-Magnet protruding the most, then this changed and the G-magnet was closest to the strings. Later, pickups with magnets of equal length and protrusion were built (**level pole-pieces**), and then again the D-magnet is most prominent "to eliminate the *chorusy warble*". A result of the staggering is the overall lower loudness of the guitar because the coil needs to move away from the string (5.4.5). There might be some reasoning in the fact that the G-string may be wound or plain, but the multitude of pickups offered today proves that staggering is not a mandatory requirement.

The material for the magnets of early Fender pickups was **Alnico-V**, an alloy from aluminum, nickel, cobalt and iron. Although literature for magnets lists exact percentages of the alloy components, considerable **variations** in the actual magnet data should be expected. The shape of the hysteresis does not only depend on chemical composition but also very much on the manufacturing process (4.4.1). Furthermore, it should be considered that due to the war effort cobalt became scarce. Today nobody can remember exactly what was actually sold ... and what was in fact used. Seth Lover, the man who developed the Gibson Humbucker, notes: "*We also used Alnico II and III, and the reason is, that you couldn't always buy Alnico V, but whatever was available we would buy as they were all good magnets*". And even if the same magnet material is used in pickups: in modern times the data of simple cylindrical magnets vary by $\pm 10\%$ – the likelihood is small that back in the good old vintage days this situation would have been any better.

Finally we need to consider the magnet-parameter which no data sheet presents with much precision: the **reversible permeability** of the magnet. This quantity describes how many times the alternating flow conductivity in the magnet is higher than that in air. Typical values range from 3 to 6; it is almost impossible to give exact data since the inhomogeneous (location-dependent) magnetic flux-density leads to a total value which is application dependent. The reversible permeability μ_{rev} determines by how much the magnet increases the inductivity of the coil. However, μ_{rev} may not be applied directly; rather, a corrected, smaller value needs to be used because the major part of the field travels through air. Replacing the magnets in a pickup may have several consequences: the string magnetization can change which results in different loudness. Changes in the field geometry could change the length of the aperture, although the connected change in treble reproduction will be mostly minor. Changes in the reversible permeability moves the pickup resonance which determines the sound, and changes of the eddy currents generated in the magnet change how much the resonance is pronounced (i.e. the emphasis or Q-factor).

Since the construction principle of the first Fender pickups was as simple as it was efficient it is still used today. Criticism was voiced only regarding two disadvantages: the sensitivity to hum (chapter 5.2, 5.7), and the missing control over individual string loudness. Though *staggered magnets* offered a kind of loudness balancing, adjustment by the musician was not possible. Pickups with adjustable magnets provided a remedy. In old **Schaller** pickups, the magnets are stuck in thin tubes which carry a screw thread on their outer surface (headless screw, grub screw). Turning these magnets will shift them axially. This trick with the grub-screw design was necessary because almost all magnetic materials (except CuNiFe) are so hard and brittle that no thread can be cut into them. Old **DeArmond** pickups as they are found in early Gretsch guitars have 6 adjusting screws which allow for axial movement of the magnets.

Gibson designer **Walter Fuller** chose a different approach to individual string-loudness control when he developed the **P-90**: this single-coil pickup utilized from 1946 featured two bar magnets below the coil. 6 ferromagnetic screws supply the magnetic flow to the strings (**Fig. 5.1.3**). Occasionally, these screws are called *nickel* screws but this does not indicate that they are (or were) made from solid nickel. It is well possible that they are regular steel screws with a nickel (or chrome) plating. The DiMarzio **SDS-1** and the **Fender-Mexico** pickups share their construction with the P-90. The common characteristic are the field-guiding pole-pieces which bridge the (re. Fig. 5.1.2) larger distance between magnet and string. The high permeability of these pole-pieces focuses the magnetic flow through the coil, however at the same time a new material is added into the magnetic circuit on top of magnet and air. The magnetic conductance of air is very small and frequency-independent. Steel (as well as nickel) conducts the magnetic flow much better than air - but only at low frequencies. For higher frequencies, which for pickups already include the kilohertz-range, **eddy currents** appear which lead to an additional attenuation (chapter. 5.9). In comparison to a Fender pickup with cylindrical magnets, a Fender pickup with bar magnets generates somewhat less treble due to the eddy currents.

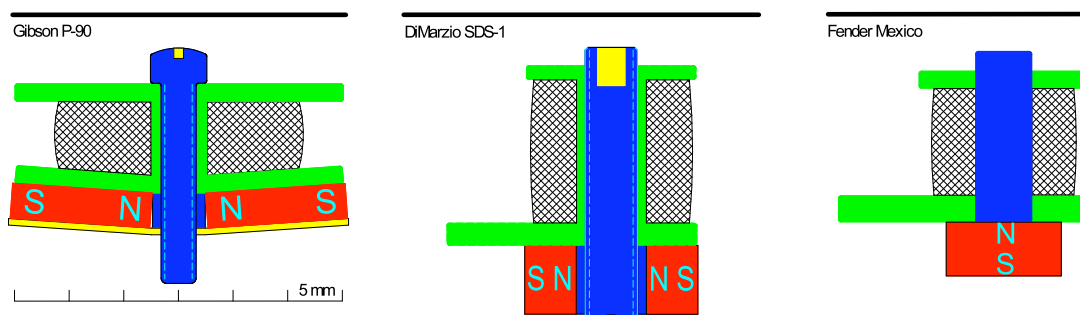


Fig. 5.1.3: Single-coil-pickups: Gibson P-90 (left), DiMarzio SDS-1 (middle), Fender Mexico (right).

Besides magnet and string, the coil **winding** is the third component in the signal generation. The first electric guitars were connected to the simplest tube amplifiers having a low input sensitivity. Consequently, the pickup had to deliver as strong a voltage as possible which necessitated a high number of winding turns: typically 5000 - 10000 turns. Exact figure quotes regarding pickup coils come with self-proclaimed guitar gurus just like year dates

come with Nostradamus. The first Stratocaster pickups had approx. 8350 turns. Or so one reads. Or knows. Thus a tad more than the Texas-Special neck pickup. That one had "only" 8200 turns. As one extends the search, tolerance specifications pop up: the magic number of 8350 turns emerges as the *mean value* between 8000 and 8700 turns [Duchossoir] which evidently represents the range of variation as it occurred back in the day. For years, pickups were wound without the use of a counter, just according to "feel" until the bobbin was full. Or belt-drive counters were used, in the hope that the inherent slippage wouldn't be too great. How else could it be explained that Duchossoir specifies 7,5 k Ω for early Telecaster bridge pickups, while Day/Rebellius report up to 11 k Ω . No sooner than 1960 does Fender introduce precise automatic winders - and still they continued to experiment with winding numbers.

Duchossoir writes in the Stratocaster booklet that the finished coils were merely monitored by measuring the coil resistance with an **Ohm-meter** having a tolerance of as high as $\pm 20\%$! Considering - on top of this - that the wire resistance per length is also subject to production tolerances, it is easy to imagine enormous variations in the winding numbers. Very generally the following holds: if for a specific pickup the number of coil turns is increased, an increase in resistance and inductivity follows. The resonance frequency drops, and the pickup gets louder. However, the resistance itself has little bearing on the transmission characteristic – the dampening effect it has remains small compared to that of other components in the circuit. If geometry and wire diameter are indeed known, it is possible to draw conclusions about the winding number from the resistance. Only given these boundary conditions there is validity in the rule: higher resistance = louder reproduction.

Next to single-coil pickups without any field-directing pole-pieces (e.g. the Stratocaster) and pickups comprising pole-pieces between magnet and string (e.g. the P-90), there is a third significant group which features guidance of the *return of magnetic flux* via pole-pieces. **Fig. 5.1.4** explains the principle based on the Fender Telecaster bridge pickup. Here, a metal plate positioned underneath the coil is - according to advertisements - supposed to shield, and to "reflect" the magnetic field. Duchossoir describes the material of this approx. 1,2 mm strong metal sheet as "tin" although this should not translate into actual sheet tin. "Tin" can also stand for tin-plated steel which is more likely to have been used since solid tin is not magnetic. Fender brochures refer to a *zinc shielding plate*, i.e. a galvanization. That's also fine. From 1951 a copper-plated steel sheet is used which is dropped in 1981 without any replacement. Presumably people at Fender realized, too, that the strengthening of the magnetic field towards the strings is so insignificant that the plate may as well be dropped. Another possible reason may have been movements of the plate which could lead to microphonic noise and feedback. Measurements do not confirm any magnetic shielding effect: the presence of the plate creates merely a difference of 0,1 dB in the interference in the parallel field. The signal level is increased by the plate by only 0,6 dB which is too little to be noticed much. Similar results occur for the resonance frequency (3% change) and the eddy current dampening (approx. 1 dB difference).

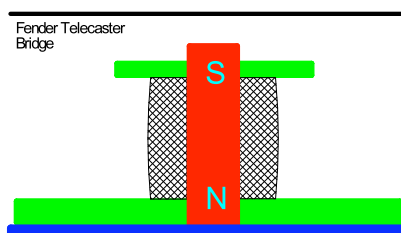


Fig. 5.1.4: Telecaster pickup with metal plate under the lower flange. The plate increases the sensitivity by 0,6 dB and reduces the resonance emphasis by approx. 1 dB; the resonance frequency drops by 3 % (due to an increase in inductivity by 6%)

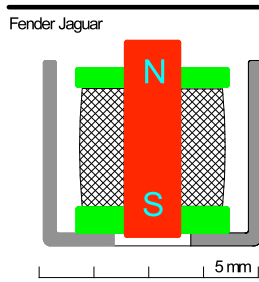


Fig. 5.1.5: Pickup with field guide sheet: Fender Jaguar.

Thoroughly continuing to think along the lines of the idea behind the Telecaster metal plate brings us very quickly to the variant Leo Fender implemented in the **Jaguar**. Here, a yoke sheet is bent around the coil winding in the shape of a "u" and the toothed upper rim focuses the field towards the strings. It didn't help much, though. At the time Fender's most expensive guitar, the Jaguar was not a commercial success. Incidentally, the pickup shielding was quite efficient, but other features of the guitar (e.g. the bridge) mercilessly bombed on the market.

Since pickup coils are comprised of extremely thin wire, they should be protected against damage by a **housing**. For the Telecaster's bridge pickup, this was accomplished by winding a thick thread over the copper winding. Simple and effective. Mechanical – not magnetic. Indeed, a magnetic field cannot be changed by a thread – but it may easily be by a metal housing (**Fig. 5.1.6**) as found with the Telecaster neck pickup (eddy currents, chapter 5.9.2.2). A motivation behind the metal housing was – on top of the physical protection – presumably the desire to shield the pickup. Mind you: no remedy can be achieved via this approach against *magnetic* interference; for that, the principle of construction would need to change (chapter 5.2, 5.3)..

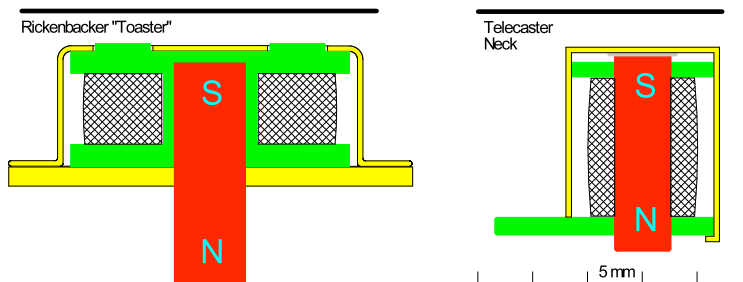


Fig 5.1.6: Single-coil pickup with protective metal casing. To avoid losses due to eddy current, the housing needs to be made of nickel silver.

A pickup installed in Gretsch guitars merits particular consideration: the "HiLoTron" (**Fig. 5.1.7**). In order to pickup as many harmonics as possible, the magnet was installed with horizontal orientation. This reasoning is elusive from a systems theory point-of-view, but apparently only the resulting sound counted for the developer – which in itself is highly purposeful, and the justification in the associated patent (chapter 5.10.5) does not really need to be correct now, does it!? The horizontally oriented magnet is also found in the Attila-Zoller-Pickup (US-Patent No. 3588311) – and to go with it again a rather unconventional reasoning in the corresponding patent. The US patent examiner was apparently not phased by that ...

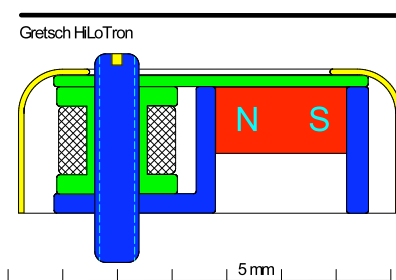


Fig.. 5.1.7: Gretsch HiLoTron (see also US-Patent No. 2683388).

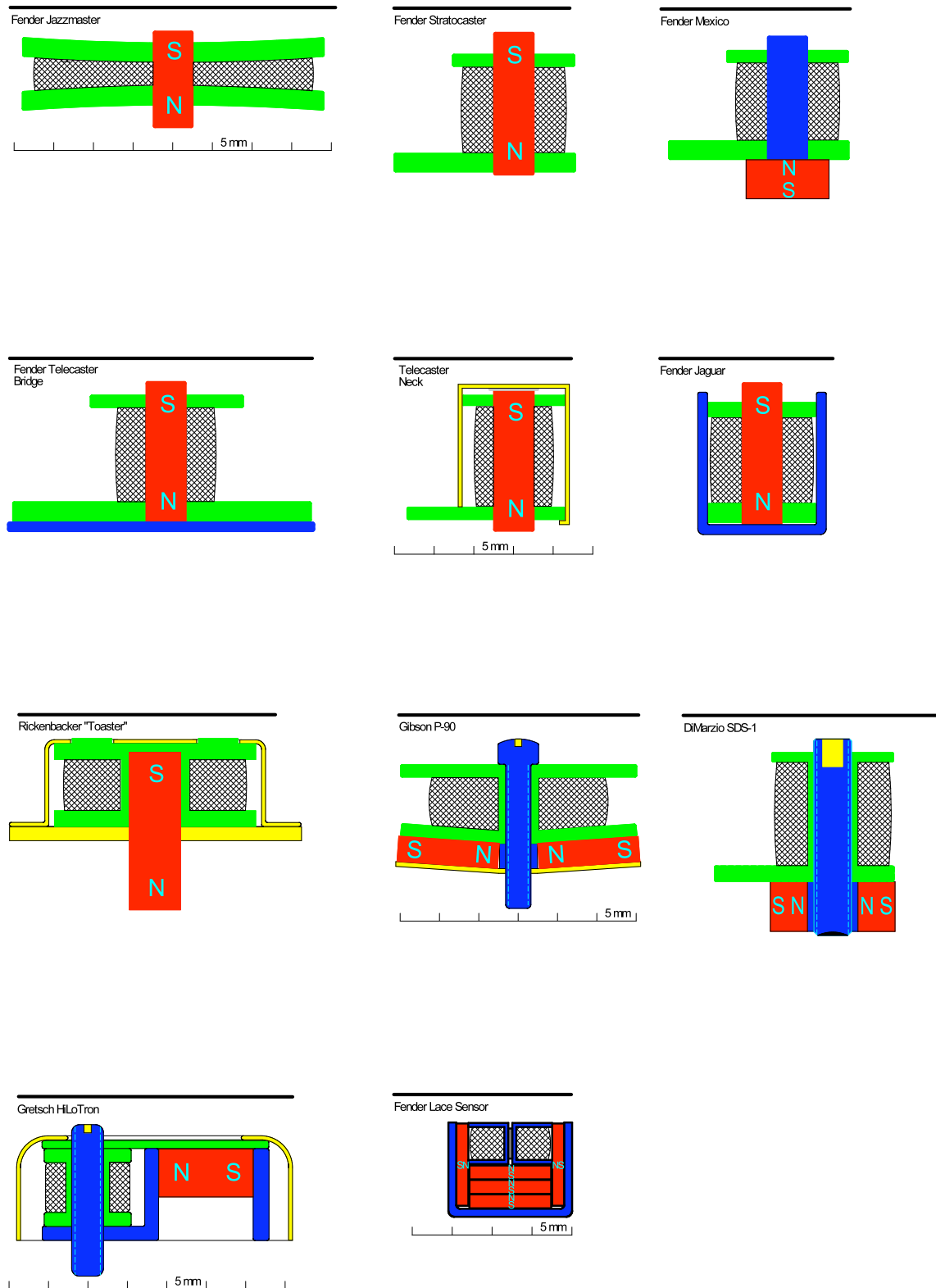


Fig. 5.1.8: Comparison of single-coil pickups